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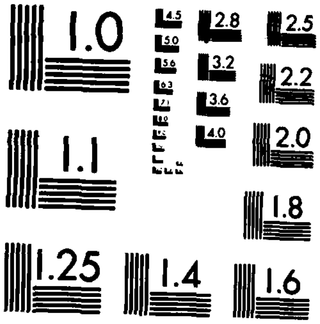
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PEARL HARBOR AND SOUTH COAST OF OAHU HURRICANE HAVEN STUDY

Prepared By:

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Science Applications International Corporation
Monterey, CA 93940

Contract No. N00228-84-C-3112

SEPTEMBER 1984

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The facilities of the ports of Honolulu and Pearl Harbor and the Naval Air Station at Barbers Point are examined as to their suitability as hurricane havens. In general, seaworthy vessels are advised to leave when a hurricane threatens. Preferred evasion tactics are discussed, and advice is given for ships unable to sortie. Comparable advice is given for aircraft at Barbers Point.

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SUMMARY

The location of the Hawaiian Islands in a region of tropical cyclone activity, the lack of sheltered facilities, and potential vulnerability to storm surge make Pearl and Honolulu Harbors poor hurricane havens. Evasion at sea is recommended for all seaworthy deep-draft vessels and submarines when the south coast of Oahu is threatened by an intense tropical storm or hurricane.

Instructions for hurricane preparedness by Naval activities on Oahu are contained in COMNAVBASEPEARLINST 3440.7, THE HAWAIIAN REGION DISASTER PREPAREDNESS PROGRAM MANUAL. Appropriate conditions of readiness for activities in the COMNAVBASE PEARL area will be set when sustained winds of fifty (50) kts are possible or expected. There is no distinction between types of tropical cyclones--the 50-kt wind criterion is the only one used for readiness conditions. Since conditions of readiness are not set for lesser winds, decisions regarding precautionary measures must be timely when a tropical cyclone approaches. Precautionary actions should include measures that would enhance a vessel's ability to get underway without delay.

Evasion plans for ships should be executed soon after COMNAVBASE PEARL has set Storm (Tropical Cyclone) Condition II, $\geq$50 kt winds expected within 24 hours. Once sea room is attained, the tactics employed to avoid or minimize the effects of the storm will depend largely on the location of and forecast for the threatening tropical cyclone and the characteristics of the vessel. A cardinal rule of seamanship is to avoid the dangerous right hand semicircle of a tropical cyclone.

Small craft should be removed from the water and firmly secured ashore above the predicted high-water line.

The safest method of protecting aircraft is dispersal to airfields away from the path of the storm. Because aircraft should be launched before field conditions deteriorate with the approach of the storm, early decision making is mandatory. The large number of aircraft assigned to NAS Barber's Point and air traffic control limitations dictate that dispersal should begin at least four hours prior to the earliest possible onset of 30-kt winds in order to have the last aircraft airborne before the 30-kt winds commence.

Pearl Harbor has been threatened by an average of 1.1 tropical cyclones each year (10 for every 9 years) during the 34 year period 1950-1983. Of these, 11 caused sustained winds of 20 kts or more in the Pearl Harbor area, and 5 caused sustained gale force winds ($\geq$34 kt). No sustained hurricane force winds ($\geq$64 kt) were recorded during a tropical cyclone passage.

The hurricane season is generally June through October, but tropical cyclones have occurred as early as February (of "Kona" origin) and as late as December. The maximum threat months are July through September with August being the most active month.

While winds from any direction could cause serious problems in the harbors, both Pearl and Honolulu Harbors are most vulnerable to southerly winds. Southerly winds would be perpendicular to most of the berths in Pearl Harbor, causing those vessels moored on the lee side of the piers and wharves to be blown off their berths. Also, a southerly wind with a fetch of any significant length could generate large waves that would pose a hazard to ships exiting Pearl and Honolulu Harbors during an emergency sortie.

The south coast of Oahu is considered vulnerable to storm surge associated with tropical cyclones passing to the west of the Pearl Harbor area.

There are no suitable hurricane anchorages on the south coast of Oahu.

1. GEOGRAPHIC LOCATION AND TOPOGRAPHY

Pearl Harbor is located on the south coast of Oahu, the third largest of eight islands in the Hawaiian group. In addition to the eight major islands, the Hawaiian Islands consist of many islets, reefs, and shoals that are strung out from southeast to northwest for 1400 n mi in the north-central Pacific Ocean (Figure 1). Pearl Harbor and the nearby Port of Honolulu, the principal deepwater commercial port of Hawaii, are located adjacent to the capital city and chief population center of the State of Hawaii, Honolulu.

Oahu island has an area of 604 sq mi and measures 39 n mi southeast-northwest between Makapuu and Kaena Points and 26 n mi south-north between Barbers and Kahuku Points (Figure 2). Oahu is mountainous and of volcanic origin as are the other major islands in the Hawaiian group. The Koolau Mountain Range parallels the northeast coast for most of its length. The part of the range between Makapuu Point and Kaneohe Bay has on its seaward side a sheer rocky cliff nearly 2000 feet high in some places. The entire range has a very jagged appearance and is cut on its inland side by deep gorges and valleys. The greatest elevation in the Koolau Range is 3,150 feet, approximately 5 miles northeast of Honolulu. The Waianae Range parallels the southwest coast of Oahu between Kaena and Barbers Points. The range has several high peaks, with 4,046 feet being the highest. Between the two mountain ranges is an extensive plain, the greater part of which is under cultivation, principally sugarcane (U.S. Department of Commerce, 1981).

The land areas surrounding Pearl Harbor and Honolulu Harbor are generally low in elevation, but rise to

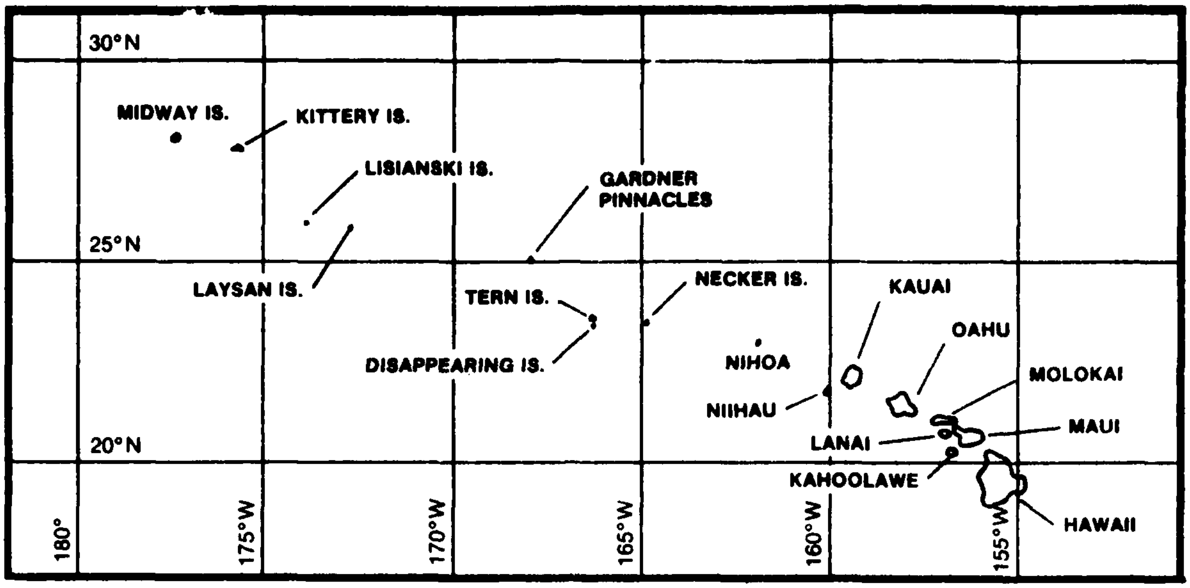

Figure 1. Hawaiian Islands.

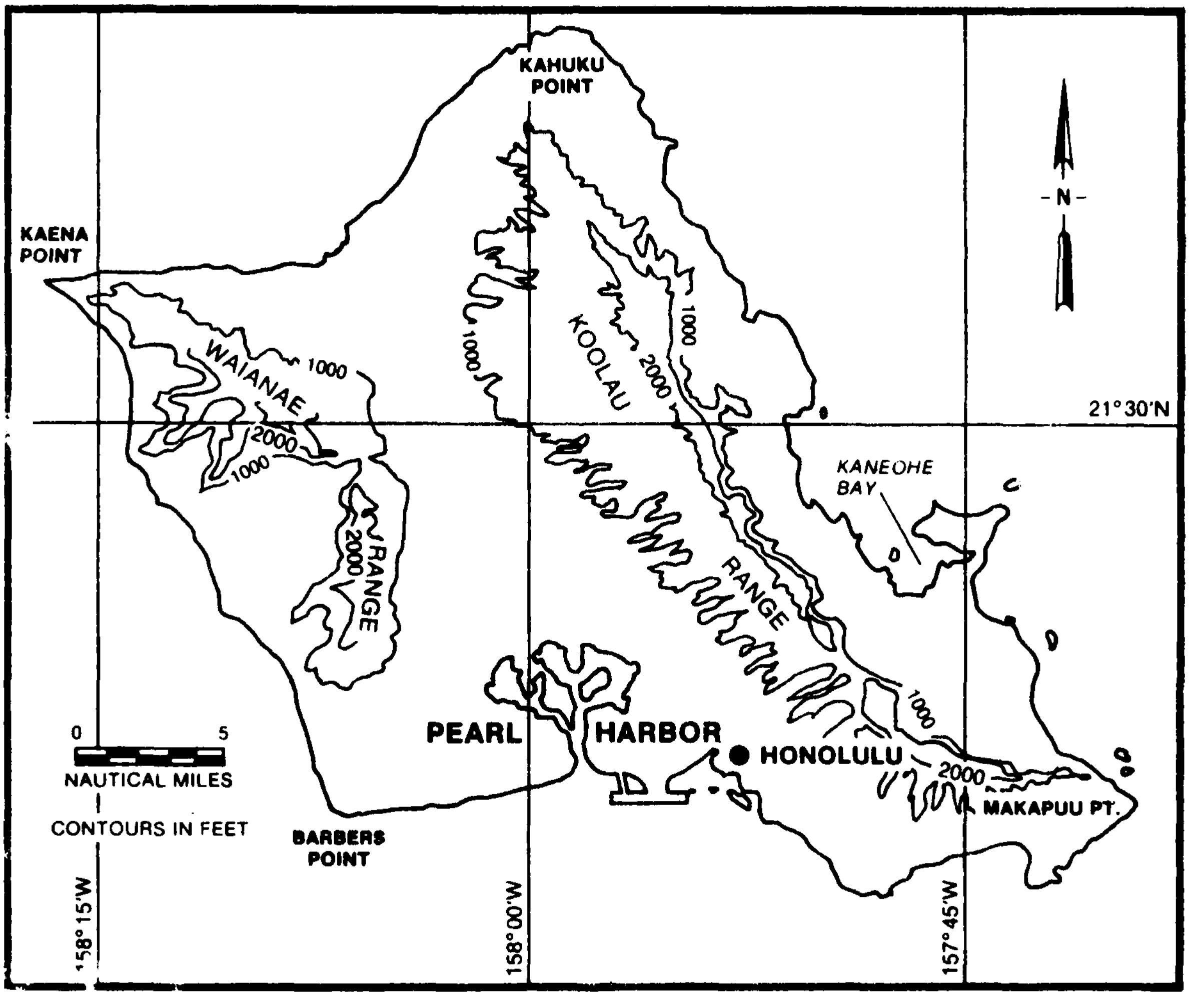

Figure 2. Oahu.

250 feet approximately 1.25 miles inland from the harbors. Once 250 feet is reached, the land slopes rapidly upward to the east of Pearl Harbor on the west side of the Koolau Range, and to the west of Pearl Harbor on the east side of the Waianae Range. The slope is more gradual north of Pearl Harbor through the valley separating the two mountain ranges, not exceeding 1000 feet at any point (Figure 3).

Naval Air Station, Barbers Point is located some 6 n mi west of the entrance to Pearl Harbor near the coast on a sloping promontory near the south end of the Waianae Range (Figure 3). The 20-foot height contour crosses the intersection of the main runway complex, with the 10-foot contour passing near the approach ends of runways 29, 4L and 4R.

In the waters surrounding Oahu, the 20 fathom depth curve is usually not far from the coral reefs that can be found around much of the island, and is seldom more than a mile from shore. The bottom generally slopes rapidly to great depths from a narrow coastal shelf (U.S. Department of Commerce, 1981).

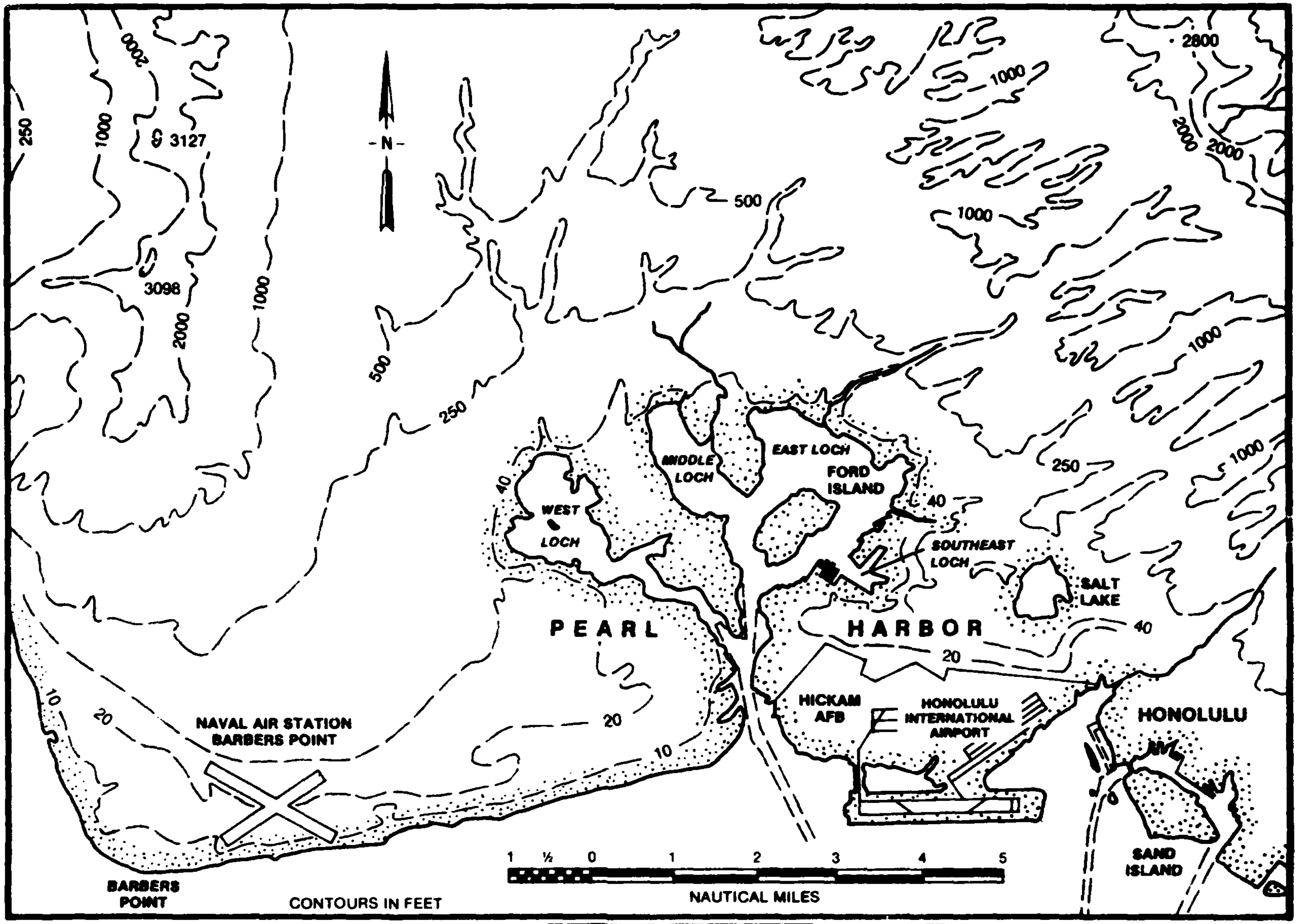

Figure 3. Topography near Pearl Harbor, Barbers Point, and Honolulu Harbor (Adapted from DMA Chart 19357 and other data).

2. THE HARBORS, APPROACHES AND FACILITIES

Several prominent landmarks mark the seaward approaches to Pearl Harbor and Honolulu Harbor from the east (Figure 4). Makapuu Head, located on Makapuu Point, the eastern extremity of Oahu, is a bold, barren, rocky headland 647 feet high that is the landfall for vessels inbound from the mainland. Koko Crater, a sharp brown cone 1,204 feet high is located 0.5 n mi from the beach, 2.6 n mi southwest of Makapuu Head. Koko Head, 4 n mi south of Makapuu Head, is a bold promontory 640 feet high with a steep seaward side. Diamond Head, perhaps the most widely known landmark on Oahu, is an extinct crater 761 feet high and is located 9 n mi southwest of Makapuu Head, and about 9.5 n mi southeast of Pearl Harbor (U.S. Department of Commerce, 1981).

Seaward approaches from the west offer less dramatic landmarks. The coastline between Barbers Point and Kaena Point consists mainly of alternating ledges of rock and stretches of white sand with spurs of the Waianae Mountains extending to most of the points. Between the spurs and ridges are heavily wooded valleys that contrast with the rocky and bare mountains.

2.1 PEARL HARBOR

The following extract from U.S. Coast Pilot 7 (U.S. Department of Commerce, 1981) is relevant:

"Pearl Harbor, is a Defensive Sea Area established by Executive Order No. 8143 of May 26, 1939. The order states in part:

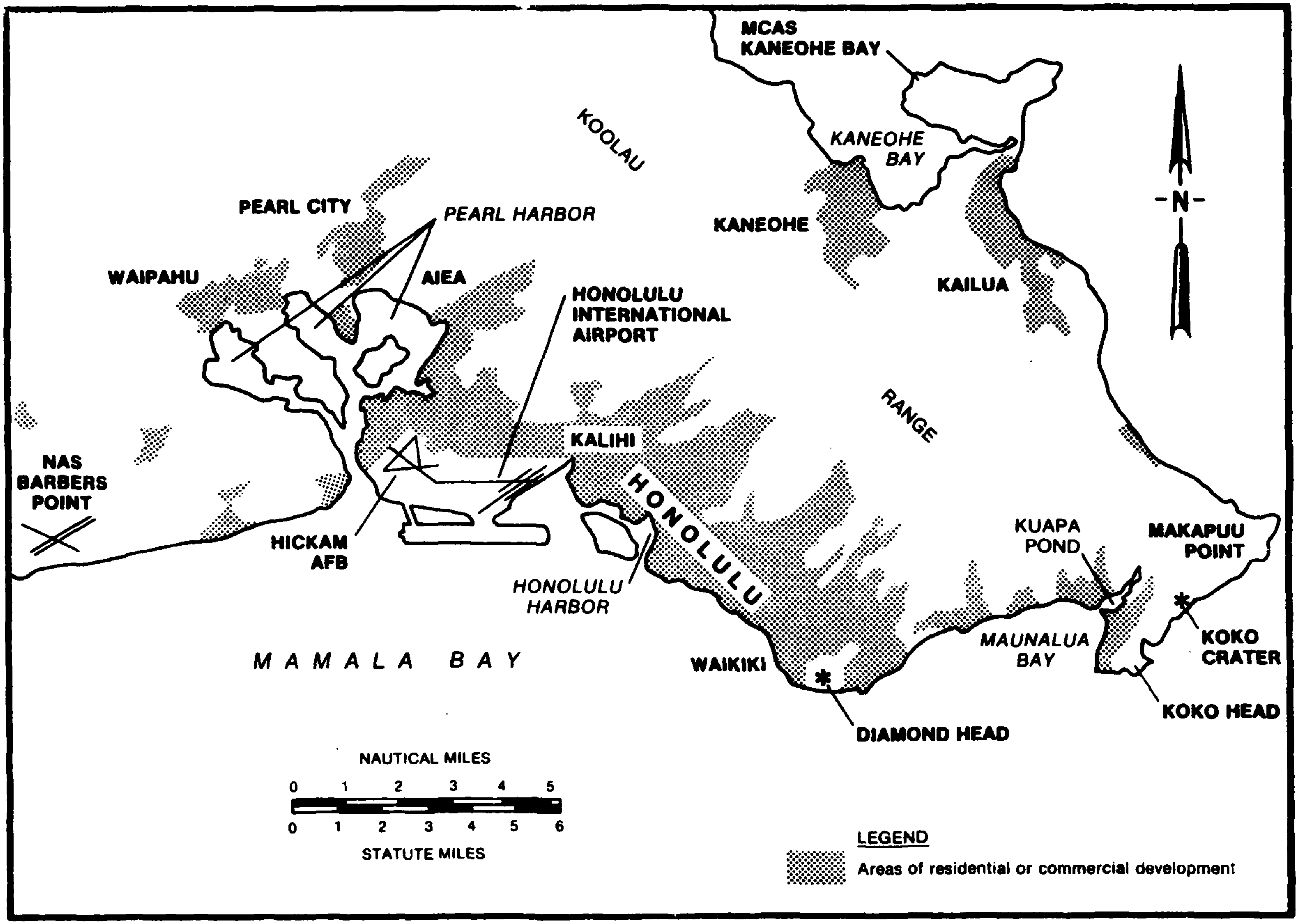

Figure 4. Southeast Coast of Oahu.

"The area of water in Pearl Harbor, Island of Oahu, Territory of Hawaii, lying between extreme high-water mark and the sea, and in and about the entrance channel to said harbor, with an area bounded by the extreme high-water mark, a line bearing S from the SW corner of the Puuloa Naval Reservation, a line bearing S from Ahua Point, and a line bearing W from a point 3 miles due S from Ahua Point, has been established as a defensive sea area for purposes of national defense, and no persons (other than persons on public vessels of the United States) are permitted to enter this defensive sea area, and no vessels or other craft (other than public vessels of the United States) are permitted to navigate in this area, except by authority of the Secretary of the Navy."

Permission to enter Pearl Harbor must be obtained in advance from Commander, Naval Base, Pearl Harbor, Hawaii 96860."

2.1.1 Approaches

Although Pearl Harbor is located in a low, flat plain, many identifiable features near Pearl Harbor exist and can be found on Chart 19357. Pearl Harbor is fan shaped with an entrance width of 400 yards (Figure 3, 4, and 5). Extending inland some 5 n mi, the main basin is divided by two peninsulas and an island into four smaller basins known as West Loch, Middle Loch, East Loch, and Southeast Loch. The entrance channel is marked by lighted and unlighted buoys and a lighted range (U.S. Department of Commerce, 1981).

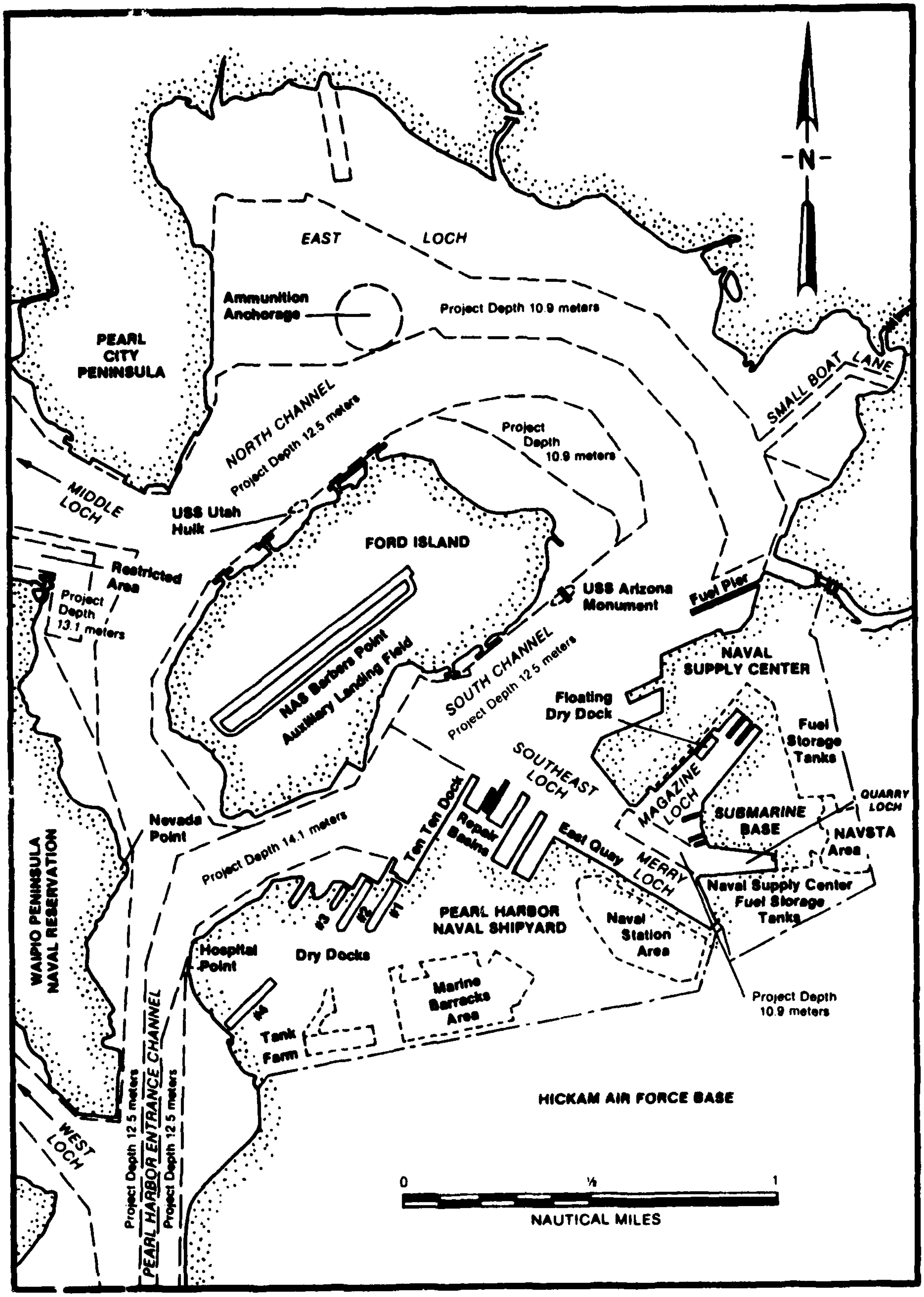

Figure 5. Major Pearl Harbor Naval Installations and Ship Channels.

An unmarked channel approach point (Papa Hotel) is located at 21°16'06"N, 157°56'25"W. The Pearl Harbor Entrance Channel commences some 4000 yds from "Papa Hotel" on a bearing of 333°36'. With an approximate width of 350 yds, the channel has an initial project depth of 15.6[1] meters near the center and 14.1[1] meters on either side of the central 100 yd main channel. As the channel approaches Nevada and Hospital Points on a northerly heading, the project depth shallows to 14.1[1] meters and remains at that depth through its eastward turn to the area adjacent to the Naval Shipyard drydocks 1,2,and 3. From a line between the end of the Naval Shipyard "Ten Ten" dock and Ford Island, the channel shallows to 12.5[1] meters and remains at that depth around Ford Island. Other waters in East Loch and Middle Loch adjacent to the main channel have project depths of 10.9[1] meters. Middle Loch is used primarily as a Reserve Fleet Anchorage. The upper half of West Loch is too shallow for deep draft vessels, but the Naval Magazine maintains berths near Powder Point at the approximate mid-point of the Loch.

2.1.2 Anchorages

Except for an explosives anchorage located just north of North Channel in East Loch north of Ford Island (Figure 5), Pearl Harbor has no anchorages due to lack of swinging room. Anchorage is available outside the harbor in 60 ft of water adjacent to the "Reef Runway" of Honolulu International Airport as indicated by the letter "A" in Figure 6. A designated explosives anchorage is located in the same general area near 21°20"N, 157°55'45"W.

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[1]Contact Pearl Harbor Port Operations for latest depths.

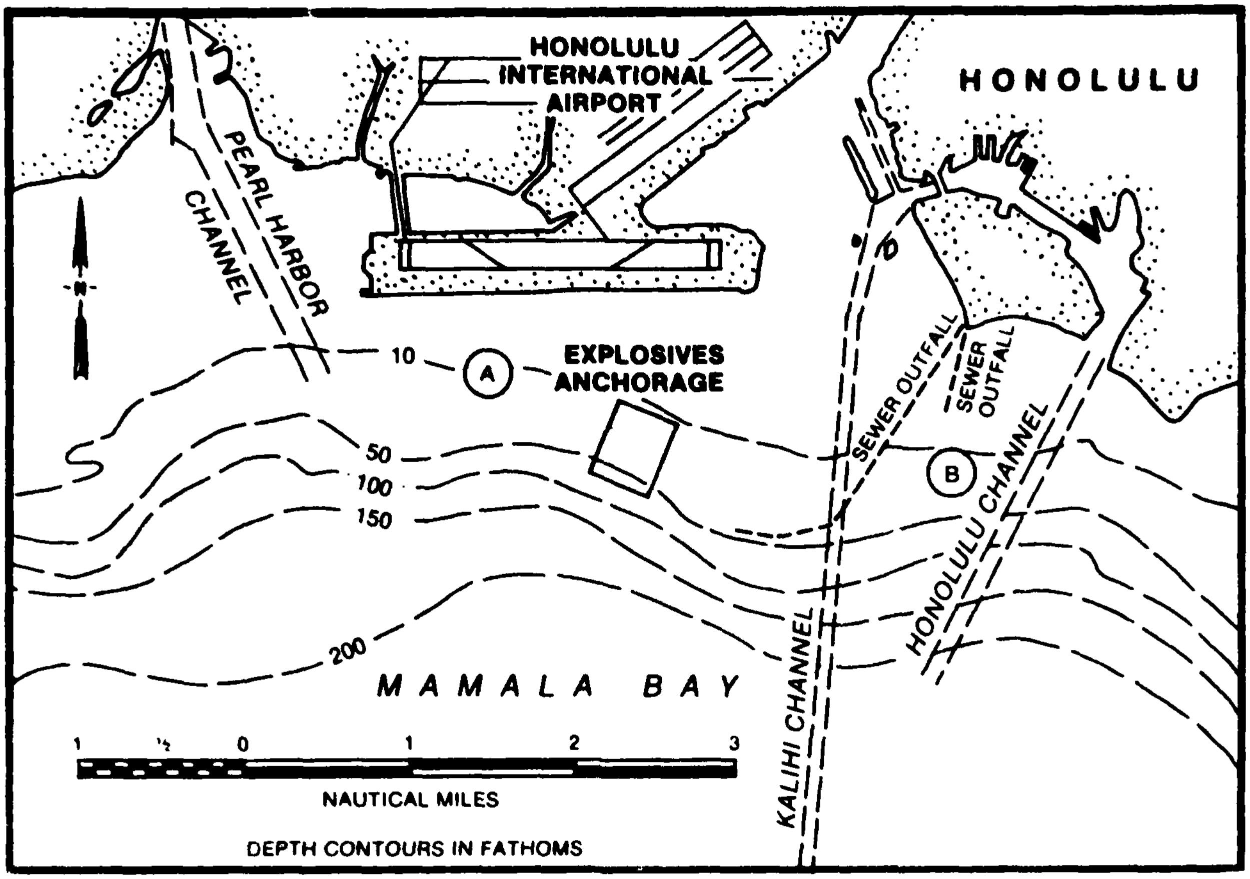

Figure 6. Entrance Channel, bathymetry contours, and anchorage areas on southeast coast of Oahu.

2.1.3 Berths

Pearl Harbor contains 101 berths inside the main channel entrance. The various command assignments are given in Table 1.

The data presented in Table 1 are subject to change as requirements change with time and periodic modifications are made. Specific data should be requested from the Pearl Harbor Port Services Office. Berth deck heights throughout the harbor are in the 10-12 foot range.

2.2 HONOLULU HARBOR

2.2.1 Approaches

Vessels approaching Honolulu Harbor have many prominent landmarks and features to assist them (Charts 19367 and 19364, and U.S. Coast Pilot 7, published by U.S. Department of Commerce, 1981) (Figure 7). Prominent features include Honolulu Harbor Entrance Light, situated 95 feet above the water on an orange and white banded flagpole type tower located on the southeast point of the entrance channel. Aloha Tower, a 193 foot cream-colored clock tower on Pier 10, is one of the most conspicuous objects in the harbor. Other easily distinguishable marks include the tall, twin white office buildings 300 yards east of Aloha Tower (particularly useful by day), the pineapple shaped 199 foot tank 0.7 mi northwest of Aloha Tower, and Punchbowl Hill, a flat topped, 500 foot rise 1 mile inland east of Aloha Tower. Of particular use at night are the horizontal blue lights of the Ala Moana Tower restaurant, 1.5 miles east of the Honolulu Harbor entrance. U.S. Coast Pilot 7 contains specific cautions regarding nighttime approaches to Honolulu Harbor since

TABLE 1. Pearl Harbor berth assignments (adapted from Naval Station Pearl Harbor Port Services Manual, 1982).

Command Assignment	Numbers	Berth Data Length(ft)	Depth (MLW)
Naval Station	A-1 to A-7	195 to 394	22
	B-15 to B-26	223 to 700	40
	F-1 to F-13	214 to 689	40
	M-1 and M-2	386	40
	M-3 and M-4	612	35
	S-15 to S-19	460 to 505	22
Naval Supply Center	H-1 to H-4	668	40
	H-5	158	15
	H-6	601	15
	K-1 to K-11	370 to 593	40
	V-1 to V-4	376 to 454	40
Naval Shipyard	B-1 to B-3	650 to 700	40
	B-4 to B-11	285 to 509	35
	B-12 and B-13	622	40
	B-14	201	40
	GD-1 and GD-2	209 to 462	40
	GD-3	80	40
	GD-4	288	25
	GD-5	60	25
	DD-1	1002	35
	DD-2	1000	45
	DD-3	497	21
	DD-4	1089	47
	O-1	762	35
	O-2	192	45
Naval Magazine	W-1 to W-3	500	30
	W-4 and W-5	500	35
Naval Submarine Base	S1-A(2)	537	35
	S-2 and S-3	250	26
	S-4 to S-9	311 to 378	35
	S-10 to S-13	375	34
	S-14	42	22
	S-20 to S-21B	418 to 551	35

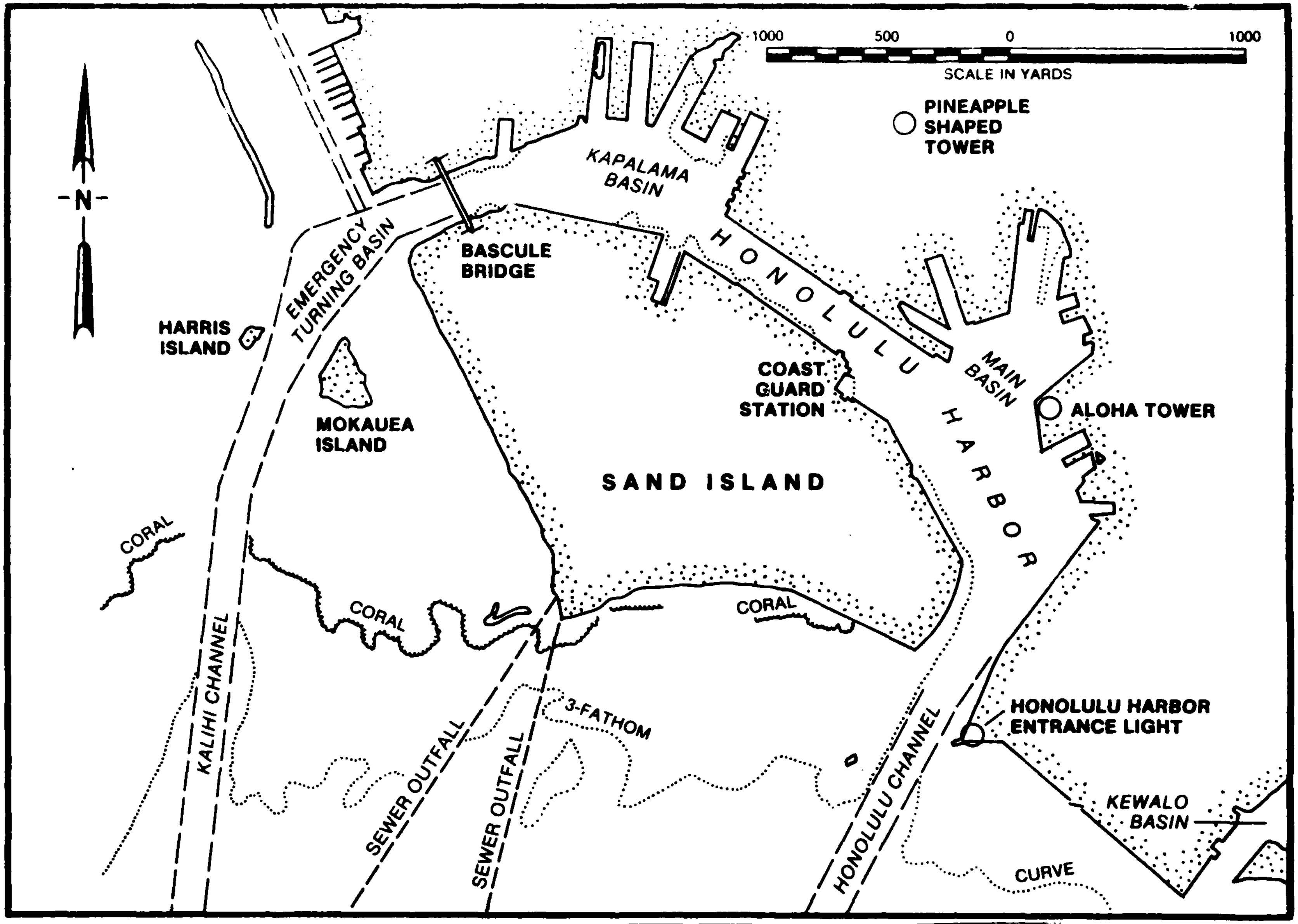

Figure 7. Honolulu Harbor (Adapted from DMA chart 19364)
NOTE: Sand Island Bascule Bridge is fixed in the closed position as of 2 December 1983.

lights of one area are easily confused with lights of another, and groundings have occurred as a result of the confusion.

The Honolulu Entrance Channel (Fort Armstrong Channel) has a 40 foot project depth[1] from the sea, thence 35 foot in the Main Basin. The project also provides for a 35 foot channel from seaward in Mamala Bay through Kalihi Channel on the west side of Sand Island to Kapalama Basin (U.S. Department of Commerce, 1981). However, as of 2 December 1983, the Kalihi Channel is no longer used as a ship channel because the bascule span of the Sand Island highway bridge was fixed in its closed position, leaving vertical and horizontal clearances of only 15 ft (at center) and 250 ft, respectively. The connecting channel (Kapalama Channel) between the Main Basin and Kapalama Basin has a 35-ft depth (Figure 7).

2.2.2 Anchorages

Recommended anchorage for deep draft Honolulu Harbor vessels, except during strong Kona winds and within 600 yards of the underwater sewer outfall lines extending seaward from Sand Island, is on a sand and coral bottom in 12 fathoms of water in Mamala Bay between the seaward ends of the two deepwater channels, as indicated by the letter "B" in Figure 6. Anchorage in the harbor basins is not practical because of the lack of swinging room. A designated explosives anchorage is located 1.3 n mi west of the seaward entrance to Kalihi Channel (Figure 6). Anchorage regulations may be obtained at the Office of the Commander, 14th Coast

[1]See Notice to Mariners and the latest editions of charts for controlling depths.

Guard District in Honolulu (U.S. Department of Commerce, 1981 and Chart 19364.) Special restricted anchorages lie in waters adjacent to the east side of Barbers Point. Specific guidelines regarding their use can be found in Port Series No. 50, published by the U.S. Army Corps of Engineers (1980).

2.2.3 Berths

The Port of Honolulu has over 60 piers and wharves around its harbor waterfront. A complete description of the facilities can be found in Port Series No. 50, published by the U.S. Army Corps of Engineers (1980). Of these, some 27 are deep-draft facilities.

Waterfront wharf facilities for deep draft vessels are located along the sides of the Main and Kapalama Basins, the connecting Kapalama Channel, and easterly side of the Fort Armstrong Channel entrance to the port. The major container handling facilities are located on Sand Island along the south side of Kapalama Channel and Basin.

Alongside depths range from 16 to 40 feet with 30 to 35 feet predominating. Deck heights vary from 6 to 8 feet. Due to the close proximity of Pearl Harbor, the Honolulu Harbor facilities are not generally used by U.S. Navy vessels. The U.S. Coast Guard maintains a base on the northeast side of Sand Island, a Government owned island bordering the seaward side of Honolulu Harbor (Figure 7) which has been built up mostly from harbor dredging.

3. HEAVY WEATHER FACILITIES AND HURRICANE ANCHORAGES

3.1 Pearl Harbor

3.1.1 Hurricane Plans and Preparation

COMNAVBASEPEARLINST 3440.7A establishes procedures for setting and responding to hazardous weather conditions of readiness for all activities under the area coordination of COMNAVBASE PEARL.

3.1.2 Tug Availability

Four YTB class tug boats of 2000 hp are available for use within Pearl Harbor. Requirements in excess of these four tugs can, with adequate notice in normal weather situations, be fulfilled by hiring civilian tugs from the Port of Honolulu tug complement. In hazardous weather situations, such as would occur with the approach of a hurricane, the civilian tugs may well be committed to other users in Honolulu Harbor and unavailable for Navy use.

3.1.3 Repair Facilities

The Naval Shipyard has all necessary facilities for making repairs to hulls and machinery, including drydocking.

3.1.4 Hurricane Berthing

The structural integrity of most of the berths in Pearl Harbor is considered by Port Services personnel to be good. Some of the berths are undergoing refurbishment at any one time in an ongoing maintenance program, so the last berths to be reworked would likely be among the strongest. The "Alpha" docks must be eliminated as potential hurricane berthing because of their exposed location near the entrance to Pearl Harbor. Most of the berths within the harbor have a northeast-southwest orientation, so winds from those directions would pose less serious problems than, say, wind with a strong southeast-northwest component that would tend to push the vessels on the lee side of the piers and wharves off their berths--an undesirable situation that can severely test the integrity of mooring lines in a high wind situation. This cross-berth component caused significant problems during the 1982 passage of Hurricane Iwa, which is discussed in Section 4 of this evaluation.

The surrounding terrain offers little protection from the effects of wind in the harbor. The greatest protection is provided by the Koolau Range to the northeast and east, and the Waianae Range to the northwest. The harbor is vulnerable to winds with a strong northerly component, as well as winds from east-southeast clockwise to west. The configuration of the harbor, i.e., fan shaped with a narrow harbor entrance, makes wave action in the harbor a relatively minor problem east of Hospital Point (Figure 5) where most of the berths are located and in West Loch near the Naval Magazine berths. The Naval Station "Alpha Docks", located opposite buoy #9 on the east side of the Pearl Harbor Entrance Channel and Naval Shipyard Dry Dock #4 are potentially vulnerable to ocean waves and swell moving northward through the Pearl Harbor Entrance Channel.

3.1.5 Hurricane Anchorages

There are no anchorages in or near Pearl Harbor considered suitable for heavy weather.

3.2 HONOLULU HARBOR

3.2.1 Hurricane Plans and Preparation

The U.S. Coast Guard Captain of the Port is the resident authority regarding the safety of the port. The Captain of the Port can, as conditions require, order ships in port at Honolulu to put to sea. Harbor personnel express the opinion that such an action would be taken only in cases where vessels would pose a threat to the safety of the harbor during hurricane passage. Hazardous cargo, such as ammonia, explosives, etc., would be the prime reason for a ship to be ordered to sea.

3.2.2 Tug Availability

The Port of Honolulu has 18 diesel powered tugs and towboats ranging from 210 to 3334 hp engaged in towing, docking, undocking, and shifting vessels in Honolulu Harbor and vicinity, as well as to other points in the Hawaiian Islands, Pacific Ocean, and the west coast of the United States (U.S. Army Corps of Engineers, 1980).

3.2.3 Repair Facilities

Honolulu Harbor has a floating drydock and a large marine railway. The specifications of this equipment is listed in U.S. Coast Pilot 7 (U.S. Department of Commerce, 1981). Machine work and the service of a 200 ton mobile crane are also available. In an emergency, large commercial vessels have been handled at the Pearl Harbor Naval Shipyard.

3.2.4 Hurricane Berthing

In general, the berthing facilities are in good repair, and ships may choose to ride out a storm in port rather than put to sea. Local personnel express the opinion that a vessel would be more at risk from flying debris (glass, sheet metal, etc.) from nearby buildings than they would from the hurricane elements themselves.

3.2.5 Hurricane Anchorages

There are no anchorages in or near Honolulu Harbor considered suitable for heavy weather use.

4. TROPICAL CYCLONES AFFECTING OAHU

A review of tropical cyclone history in the central north Pacific Ocean as done by Shaw (1981) yields a paucity of data for the years prior to 1950. Although extensive research was done, only 19 storms are documented for the 118 year period of 1832-1949, an average of less than one storm per 6 year period. Recent advances in tropical cyclone detection and observation such as more or less continuous geostationary environmental satellite coverage, has shown that while some years or multiple year periods are devoid of significant activity, other years have many tropical cyclones. For example, 8 tropical cyclones were recorded in the central north Pacific Ocean during 1962. The data recorded during 1950 and later years provides a more meaningful data base with which to work, and were used to determine the statistics presented in the following discussion.

An examination of the relevant characteristics of tropical cyclones, such as track, speed of movement, intensity, month of occurence, etc., may yield some insight into their typical behavior. This enhanced background knowledge and understanding will allow attention to be focused on those storms most likely to pose a serious threat to the southeast coast of Oahu in general, and to Pearl and Honolulu Harbors specifically. It is stressed, however, that the historical behavior of individual storms and their impact on a given area should not be used as a reliable guide to the detailed behavior and impact of a particular storm as it approaches Oahu.

Historically, Hawaii has rarely been seriously affected by hurricanes. As documented by Stearns (1960), the period 1903-1959 saw only three instances where "the Hawaiian

Islands came under the influence of a fully developed hurricane." These were Hiki in August 1950, Nina in December 1957, and Dot in August 1959. The list was extended to four when Hurricane Iwa passed close by the islands in November, 1982 (Rosendal, 1983 and Chiu, et al., 1983). The infrequency of occurrence in no way diminishes the possibility of a hurricane posing a serious threat to the islands, but it does, however, cause naivete' with respect to the potential for hurricane damage.

4.1 CLIMATOLOGY

For the statistical purposes of this study, any tropical cyclone that approached to within 360 n mi of Pearl Harbor is considered a threat. Many of the tropical cyclones within this radius had no significant effect on the weather of Oahu, so to some extent this criterion is arbitrary. Track information has been extracted from Shaw (1981), Chun (1983), Rosendal (1983) and U.S. Navy sources. Except where otherwise indicated, the climatological figures have been derived from data for the period 1950-1982 inclusive.

In an average year, approximately three tropical cyclones will either form in or propagate into the central North Pacific region, defined by the National Weather Service as bounded by 140°W on the east, 180° on the west, and the equator on the south. Of these, two can be expected to be of tropical storm (wind 34-63 kts) or hurricane (wind $\geq$64 kts) strength. Since 1950, they have formed in all months from July through November. Prior to 1950, tropical cyclones were also recorded in the months of May and December (Shaw, 1981). A March storm has also been included in this evaluation. It started as a "Kona" cold-core storm in March 1951, but later developed tropical (i.e., warm core) characteristics. This

March storm is discussed in the Local Area Forecaster's Handbook published by the Naval Western Oceanography Center (1981). For the purpose of this evaluation, the month of occurrence is that month in which the tropical cyclone entered the 360 n mi threat radius of Pearl Harbor.

Of the 37 tropical cyclones that threatened Pearl Harbor during the 34 year period, 1950-1983, 31 (84%) occurred during the months of July, August, and September, with the peak threat in August. Hurricane strength storms (winds $\geq$64 kts) were recorded most often during July and August with 5 of 8 (63%) occurring during those two summer months (Figure 8).

Figure 9 displays the tropical cyclones as a function of the compass octant from which they entered the 360 n mi radius circle around Pearl Harbor. Because one storm formed within the 360 n mi radius, only 36 storms are assigned approach directions. A second storm, the March 1951 "Kona" storm which developed tropical characteristics and was discussed above, formed with the 360 n mi radius but exited and reentered, so a reentry direction was determined and used. It is evident from Figure 9 that the major threat from tropical cyclones is from the east, southeast, and south, with 84% of the storms coming from those directions.

An average of 1.1 tropical cyclones per year passed within 360 n mi of Pearl Harbor during the period 1950-1983. Less than 1 in 4 (8 of 37) have been of hurricane strength while within the 360 n mi distance. One way of interpreting the hurricane occurrence is to expect a hurricane strength storm to pass within 360 n mi of Pearl Harbor once each 4 to 5 years. Such uniformity seldom happens in nature, however. For example, during the 18-year period from 1960-1977

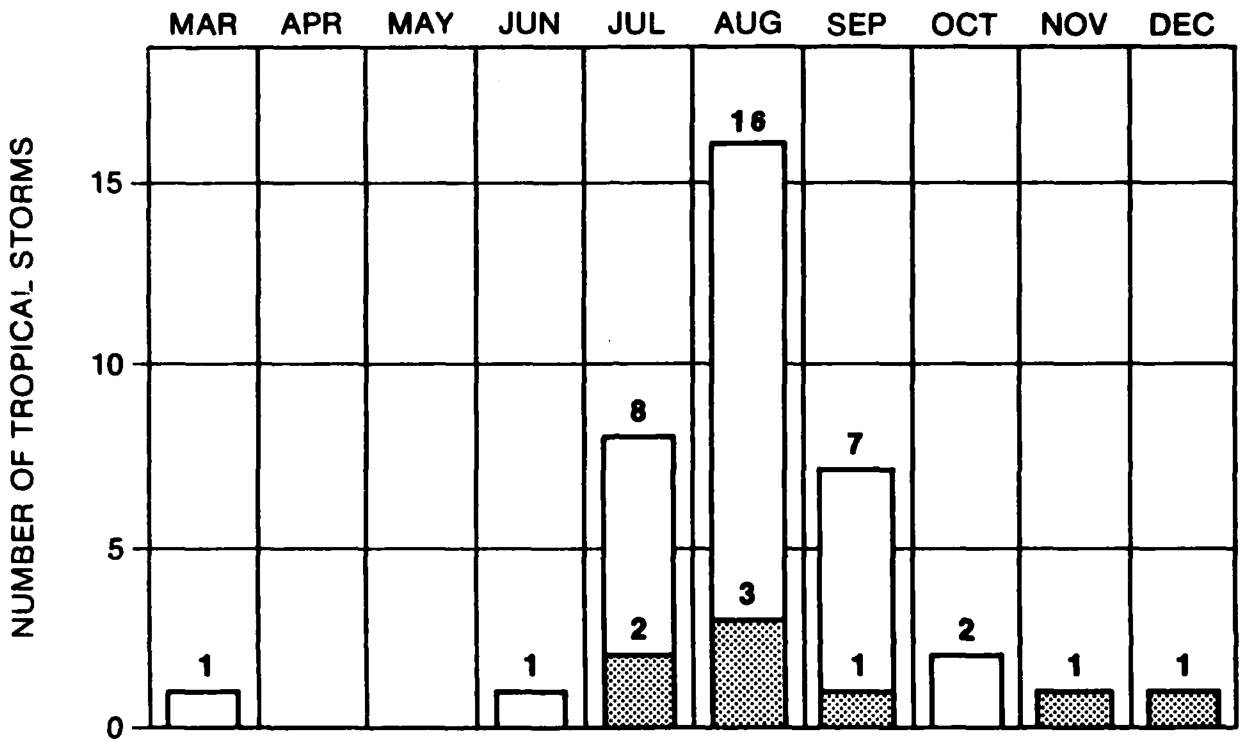

Figure 8. Seasonal distribution of tropical cyclones passing within 360 n mi of Pearl Harbor (March-December) and based on data for the period 1950-1983, inclusive. Monthly totals are shown above each column; numbers of threats of hurricane intensity (while within 360 n mi threat radius) shown by shaded areas.

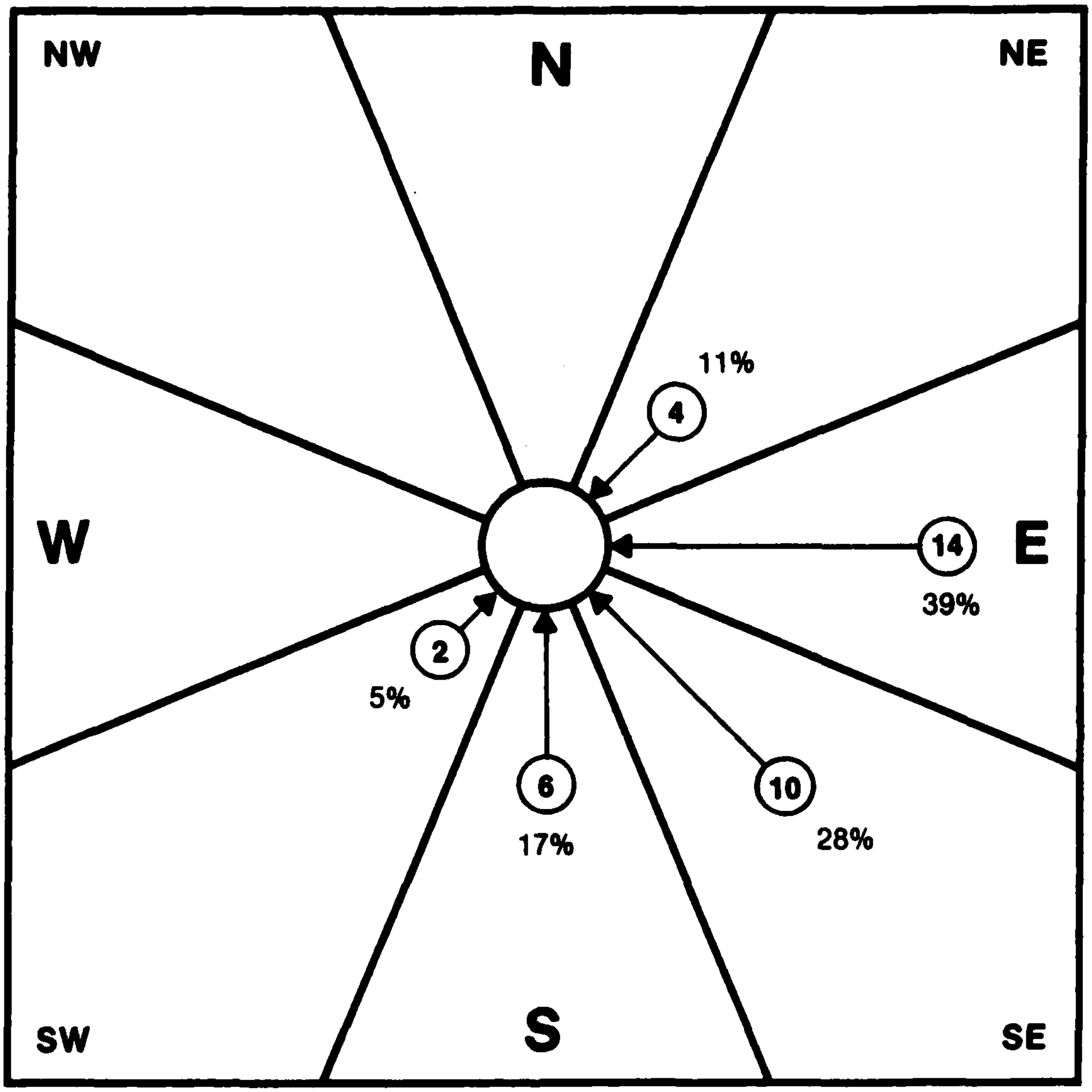

Figure 9. Directions of approach of tropical cyclones that passed within 360 n mi of Pearl Harbor during the period 1950-1983. Numbers of storms approaching from each octant are circled; percentage figures are percent of total sample approaching from that direction. (One tropical cyclone formed within the 360 n mi radius so a direction of approach is not applicable.)

inclusive, no hurricane strength storms came within 360 n mi of Pearl Harbor, while two of three tropical cyclones which entered the threat radius in 1957 were of hurricane strength.

Figures 10 through 14 show the tracks of all tropical cyclones of record which came within 360 n mi of Pearl Harbor. An examination of the 37 tracks depicted clearly shows the main threat axis to be from the east-southeast. This is to be expected, however, since a majority of the storms which threatened Pearl Harbor originated in the eastern Pacific Ocean east of 140°W. A study of the 10-year period 1965-1974 by Renard and Bowman (1976) showed that while some 70% of the tropical cyclones which formed in the eastern Pacific had dissipated (or reached their westward terminal positions) before they reached 140°W, the remainder followed a track that carried them to the Hawaiian Islands area, with the main track axis east-west just north of 15°N. The dissipation percentage increased to about 90% by the time 155°W was reached.

Figure 15 is a statistical summary of threat probability for the years 1950-1982. The solid lines represent the "Percent Threat" for any storm location. The dashed lines represent approximate approach times to Pearl Harbor based on the climatological approach speed for a particular location. For example, a tropical cyclone located at 15°N, 140°W has about a 40 percent chance of passing within 360 n mi of Pearl Harbor. If its speed of movement remains close to the climatological norm, it will reach Pearl Harbor in 4 to 4 1/2 days (96-108 hours).

For comparison, Figure 16 is a statistical summary from the same data base (1950-1982), but it considers the

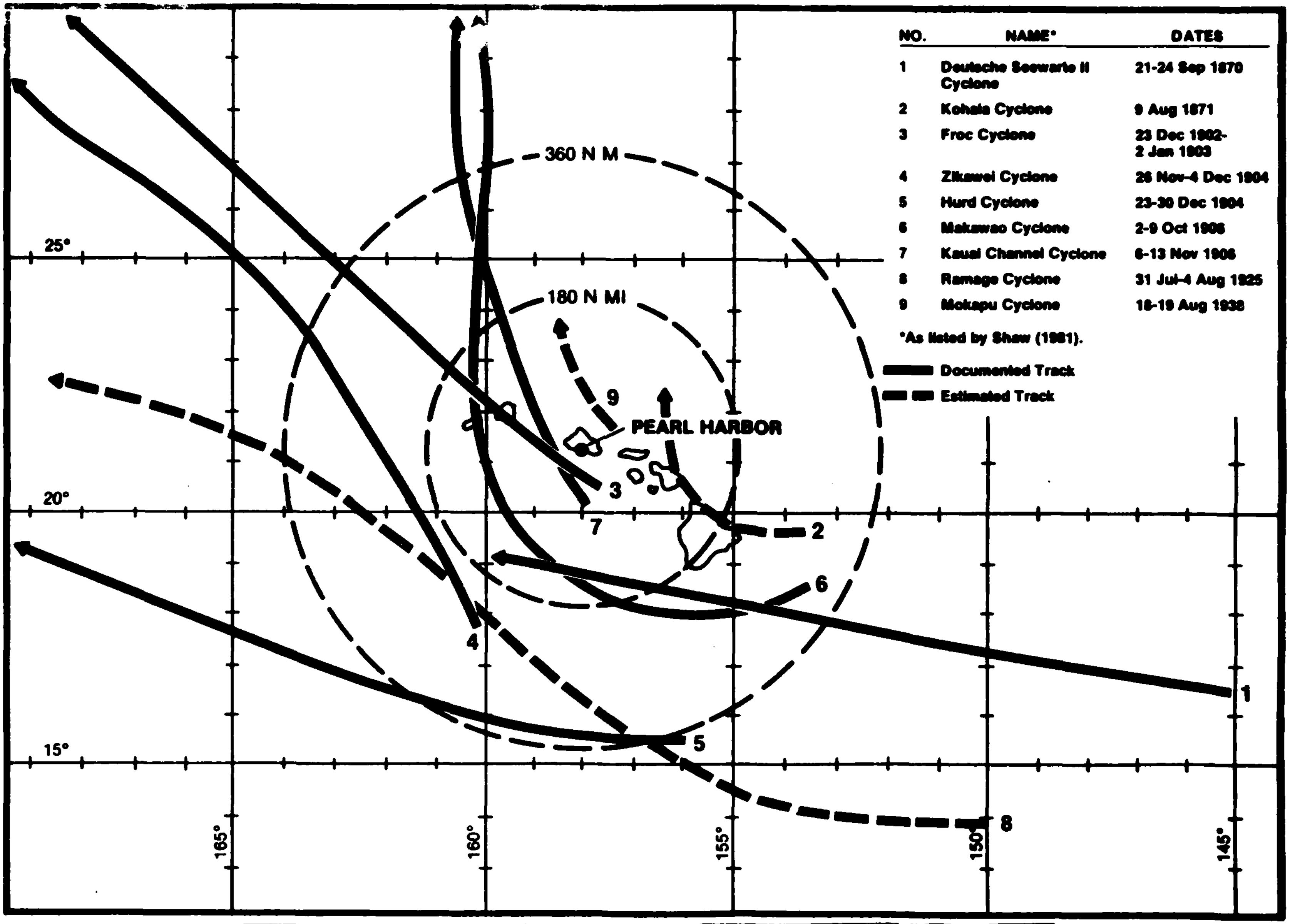

Figure 10. Tropical cyclone tracks for the period 1832-1949 which came within 360 n mi of Pearl Harbor (after Shaw (1981)).

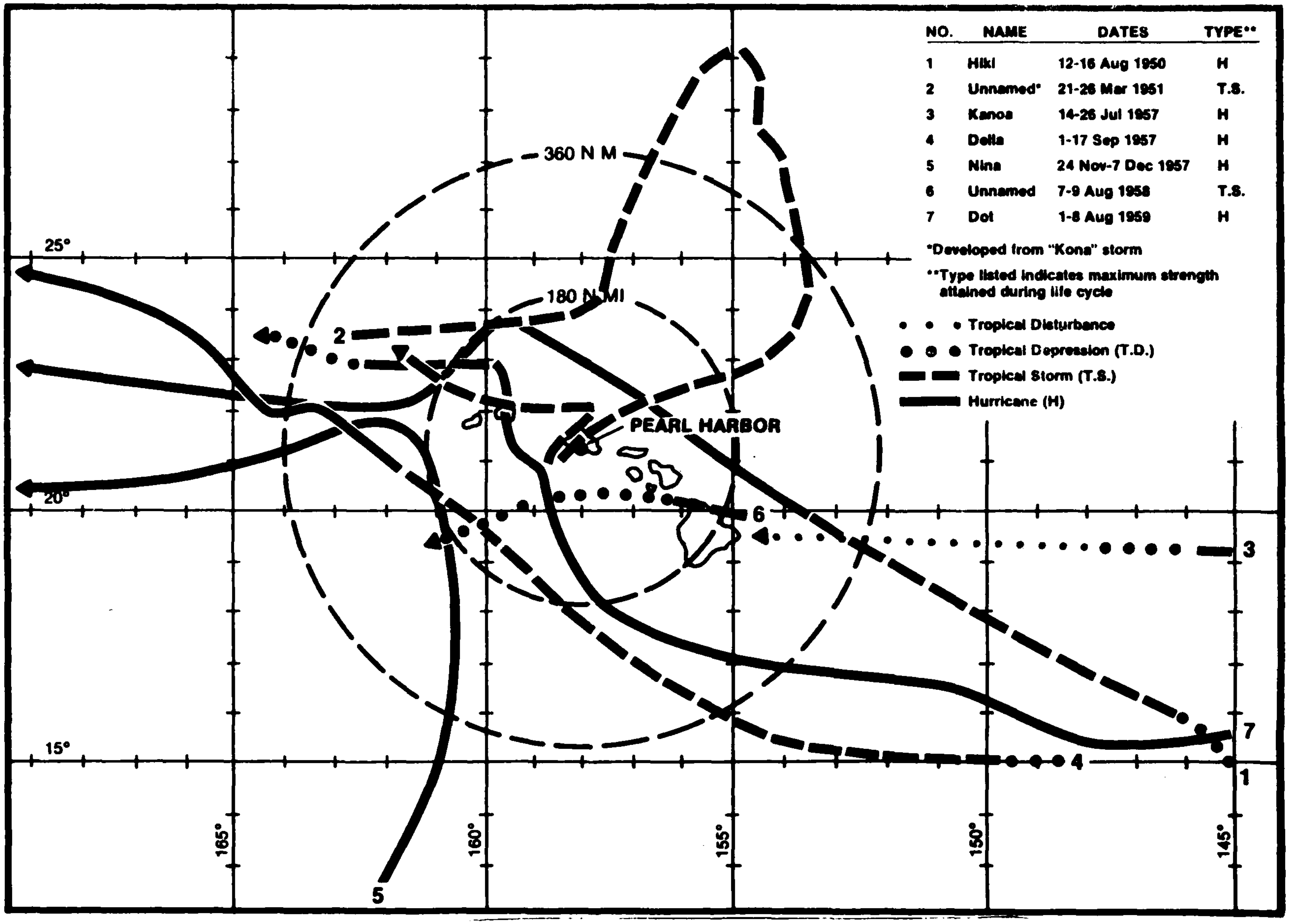

Figure 11. Tropical cyclone tracks for the period 1950-1959 which came within 360 n mi of Pearl Harbor (after Shaw (1981) and other sources).

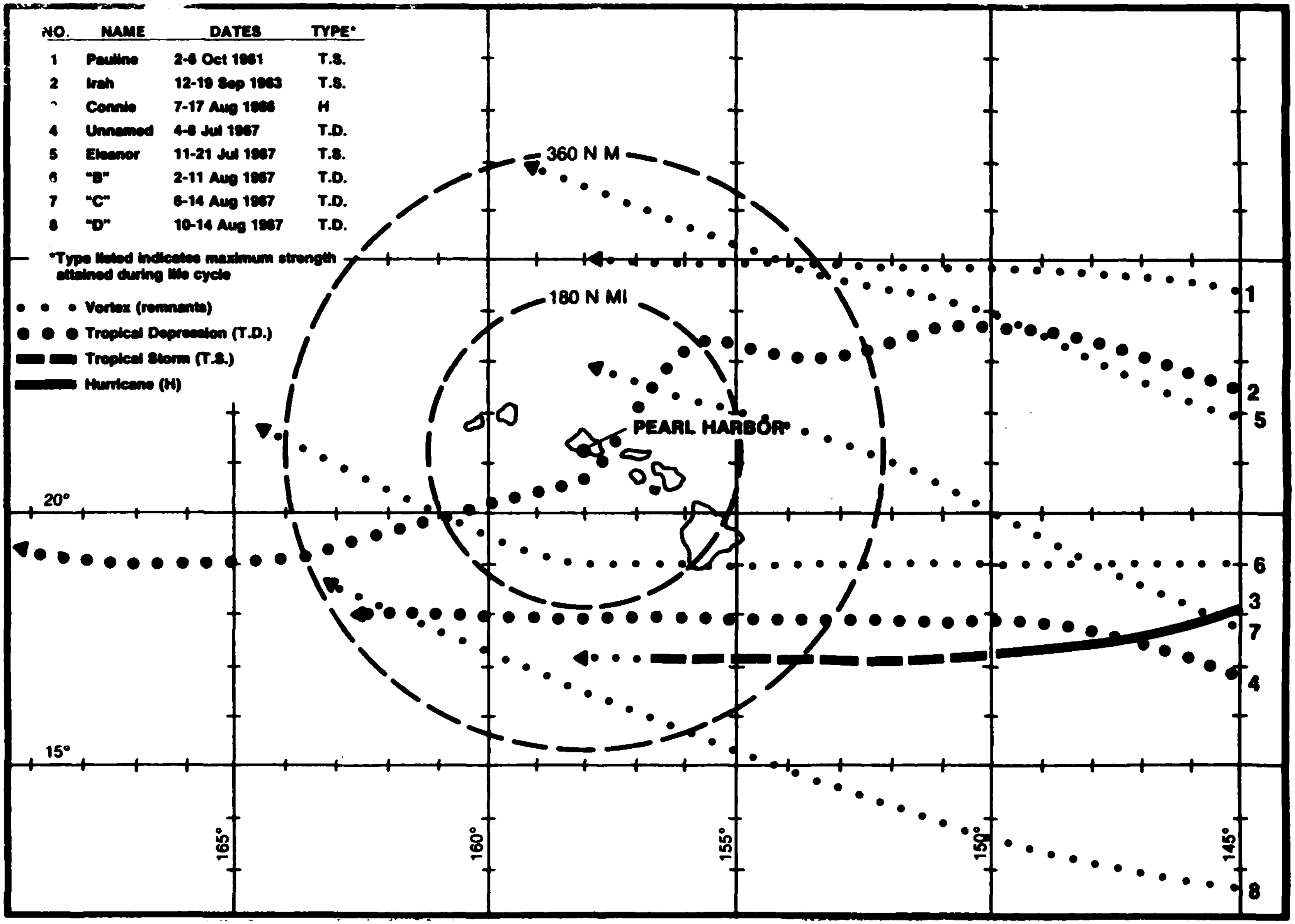

Figure 12. Tropical cyclone tracks for the period 1960-1969 which came within 360 n mi of Pearl Harbor (after Shaw (1981)).

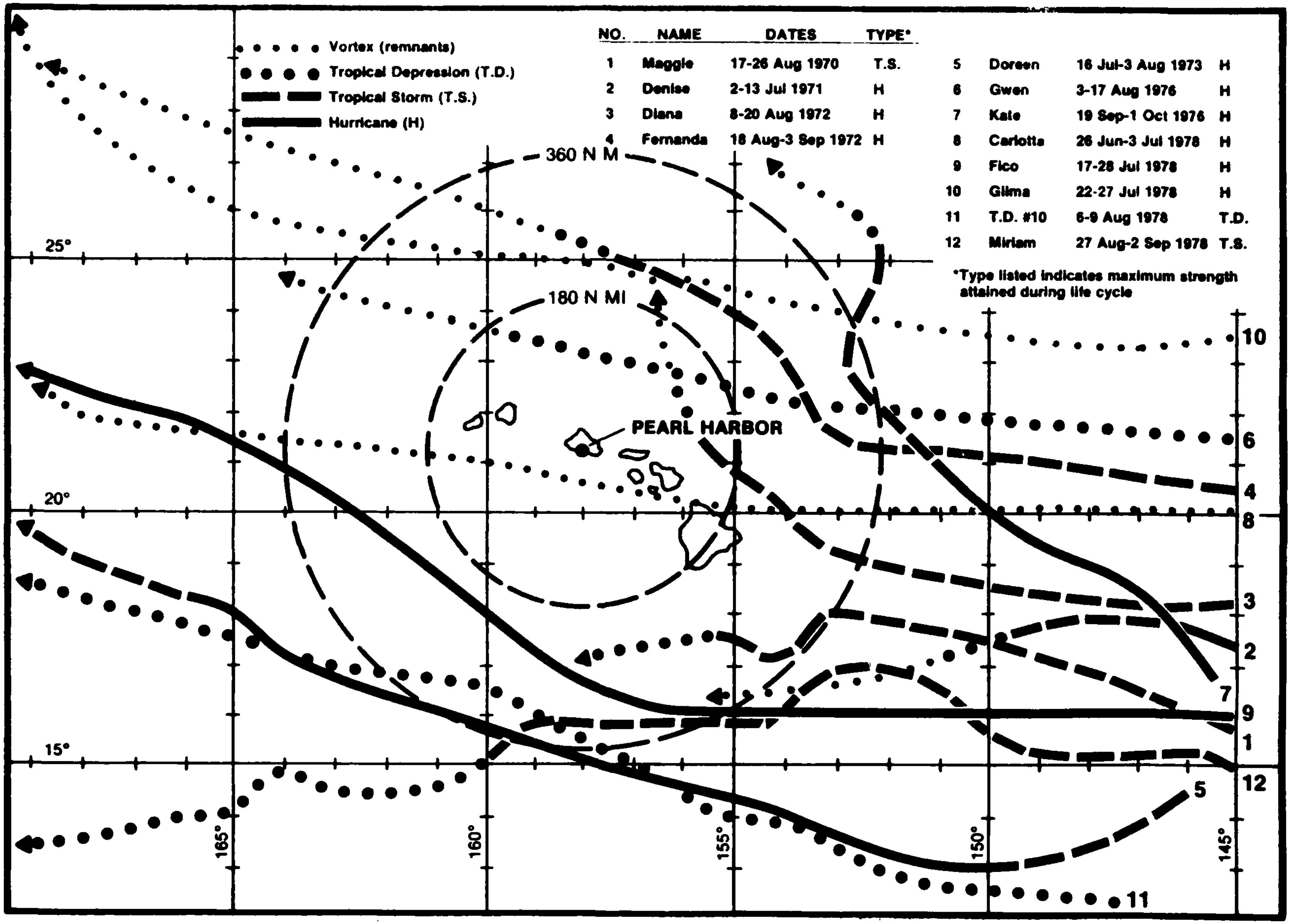

Figure 13. Tropical cyclone tracks for the period 1970-1979 which came within 360 n mi of Pearl Harbor (after Shaw (1981)).

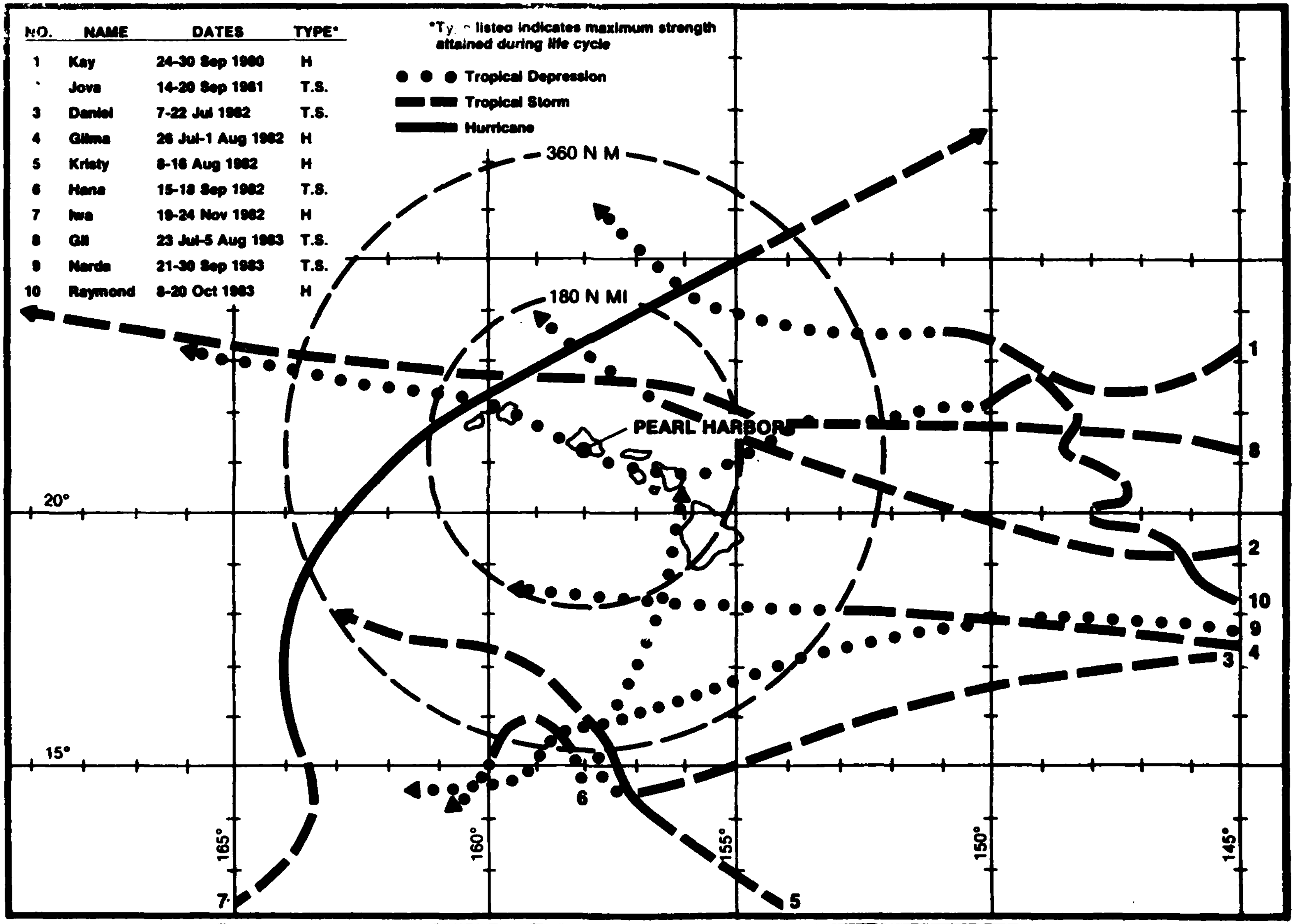

Figure 14. Tropical cyclone tracks for the period 1980-1983 which came within 360 n mi of Pearl Harbor (after Chun, 1981 and 1983; Lee, 1982; and other sources).

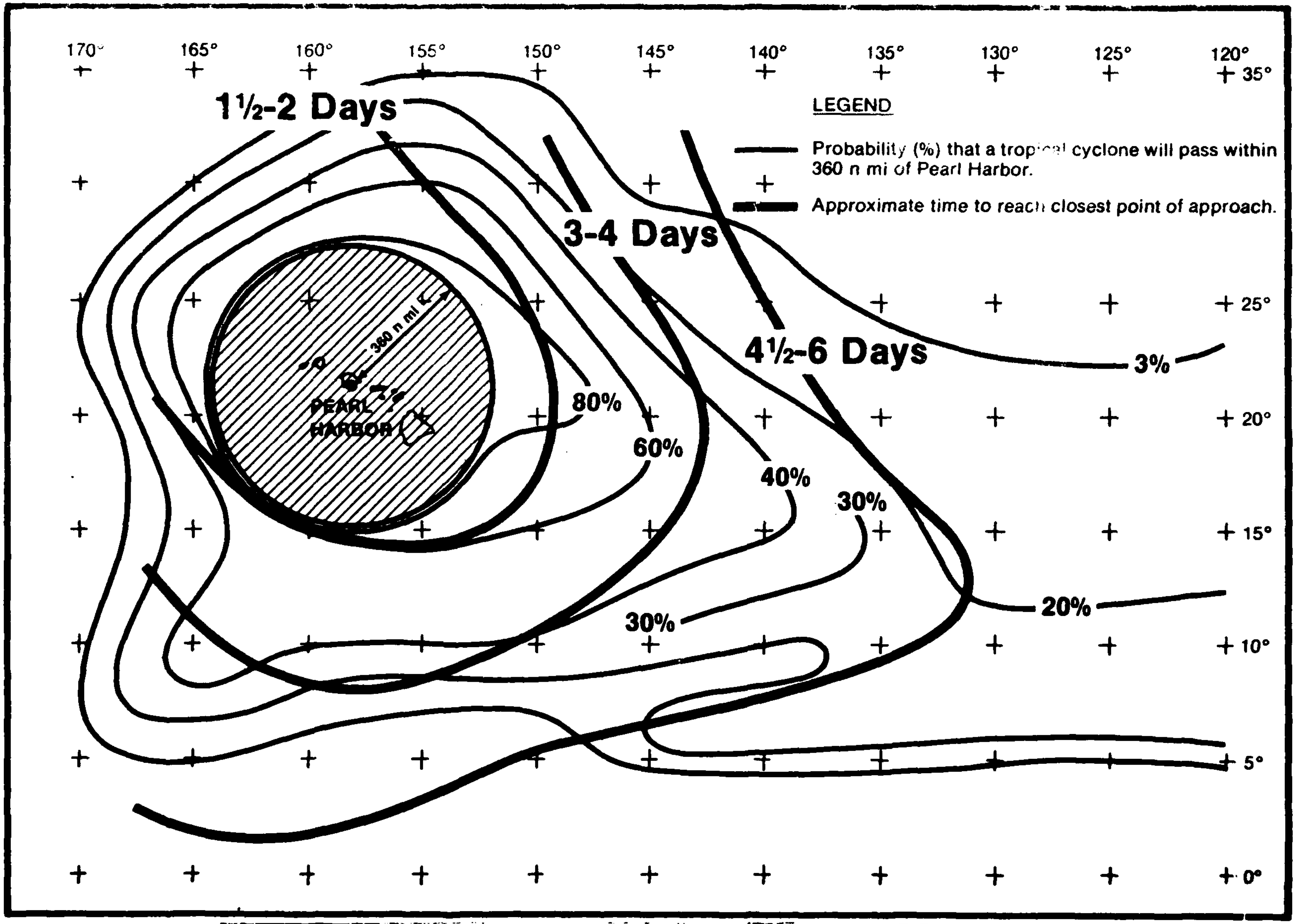

Figure 15. Probability that a tropical cyclone will pass within 360 n mi of Pearl Harbor (based on data for the period 1950-1982, inclusive).

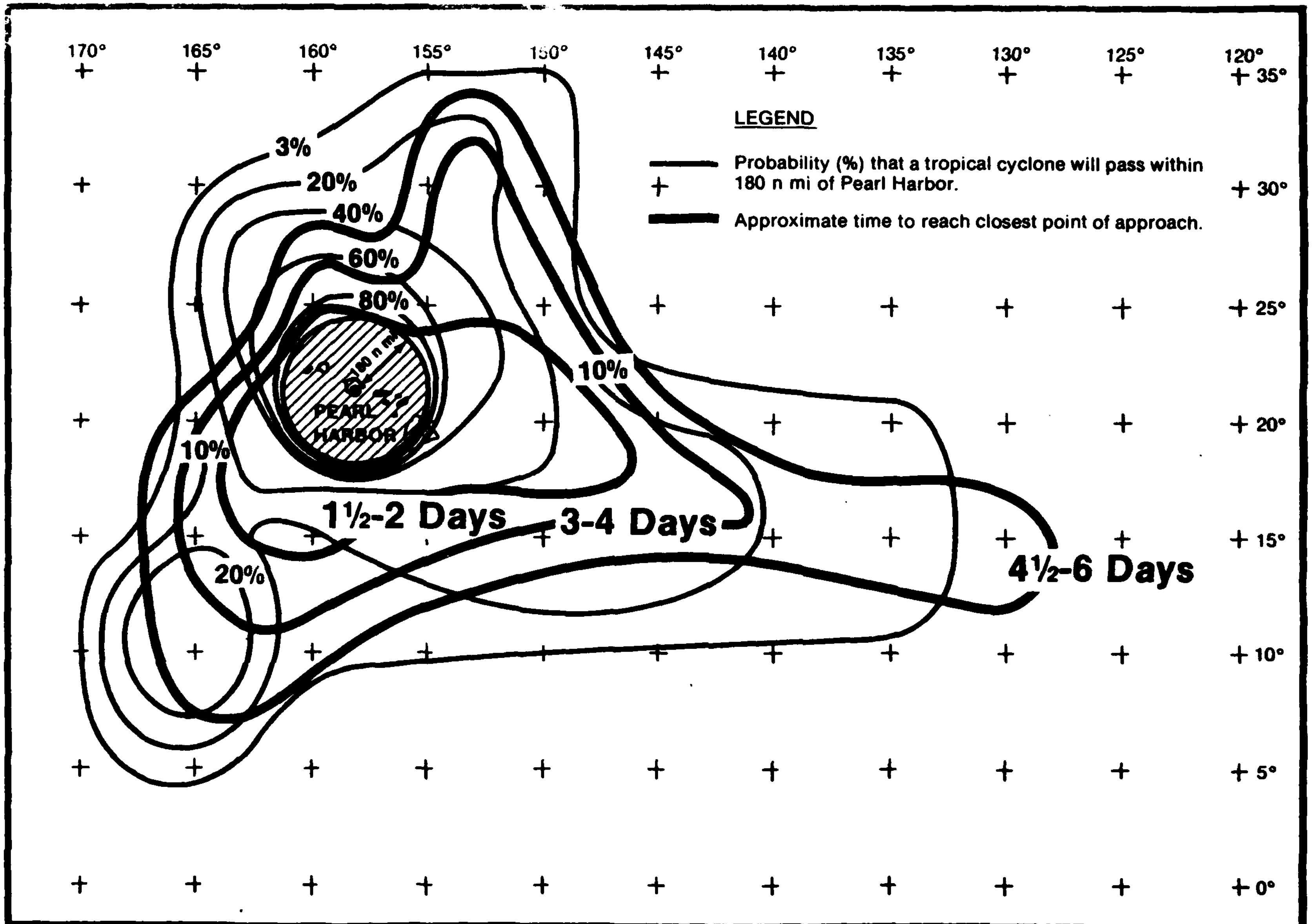

Figure 16. Probability that a tropical cyclone will pass within 180 n mi of Pearl Harbor (based on data for the period 1950-1982, inclusive.

threat radius as 180 n mi, vice 360 n mi as in Figure 15. By reducing the threat radius, the number of tropical cyclones penetrating the radius is reduced. Based on this reduced sample, a tropical cyclone located at the same position previously discussed, 15°N 140°W, has only about a 10 percent probability of passing within 180 n mi of Pearl Harbor, and would still take 4 to 4 1/2 days (96-108 hours) to reach Pearl Harbor if the speed of movement did not vary from the climatological norm. Because of the reduced data sample, the figures for the 180 n mi threat radius are not considered to be as reliable as those for the 360 n mi threat radius.

An examination of both figures shows similar threat axes, with the primary threat coming from the east-southeast, and a secondary threat coming from the south-southwest. The latter threat is due to the approach of two significant storms from that basic direction, Hurricane Nina in 1957, and Hurricane Iwa in 1982.

Typical speeds of movement for tropical cyclones in the central Pacific Ocean varies from 8 to 14 kts during the main threat months, with 8 to 9 kts most likely early in the season (June) increasing to 11 to 14 kts during August. The speeds computed for 23 of the 37 tropical cyclones occurring within 360 n mi of Pearl Harbor during the period 1950-1982 are as follows: Five July storms averaged 12 kts while within 500 n mi of Pearl Harbor, eleven August storms averaged 10 kts, and four September storms averaged near 8 kts. The average speed of movement of Hurricane Iwa in November 1982, while within 500 n mi of Pearl Harbor was 19 kts and it attained a speed of about 30 knots when it was near its CPA to Oahu.

4.2 LOCAL WEATHER CONDITIONS DURING TROPICAL CYCLONE PASSAGE

The primary sources of the weather data examined in this discussion were the hourly observations from the National Weather Service Office at Honolulu International Airport and the Naval Air Station, Barbers Point. The sites and periods of records for hourly observations are as follows:

WBAS HONOLULU 1950-1966
WBFO HONOLULU 1970-1971
WSFO HONOLULU 1972-1982
NAS BARBERS POINT 1950-1959
NWSED BARBERS POINT 1966-1978
NOCD BARBERS POINT 1980-1982
NAS/NOCD BARBERS POINT 1982

During the 34 year period, 1950-1983, 37 tropical cyclones passed within 360 n mi of Pearl Harbor. Table 2 lists various aspects of those storms that caused significant wind/weather on the south coast of Oahu as recorded in the observations discussed above. Based on the data in Table 2, sustained gale force winds ($\geq$34 kts) can be expected from approximately 1 out of every 7 tropical cyclones passing within 360 n mi of Pearl Harbor. The same data reveal that sustained hurricane force winds ($\geq$64 kts) were not experienced at either of the recording stations during the 34 year period 1950-1983.

Figure 17 depicts track segments of each of the 11 tropical cyclones when winds $\geq$20 kts were recorded in the Pearl Harbor area. Figure 18 depicts the wind direction distribution for the same 11 storms while winds $\geq$20 kts were recorded. It is interesting to note that while winds were

TABLE 2. Wind and precipitation data for those tropical cyclones that significantly affected the south coast of Oahu during the period 1950 through 1983. Occurrences when the sustained wind remained less than 20 kts are not included.

TROPICAL CYCLONE DATA			RELATED WEATHER IN PEARL HARBOR AREA			
DATE AND NAME	DIR/CPA (N Mi)	TYPE AT CPA	MAX SUSTAINED WIND AND GUSTS (Kts) Honolulu*	Barbers Pt.	HONOLULU* PRECIPITATION Total (IN.)	REMARKS
5 Aug 50 HIKI	NE/84	H	WSW 30 GUST 37	WNW 25 GUST 35	0.72	
25-27 Mar 51	SW/10	T.S.	ESE 43 GUST 51	E 44 GUST 51	4.54	Precip amount for 25 Mar missing from total
30 Nov-2 Dec 57 NINA	WSW/186	H	NE 45 GUST 62	ENE 32 GUST 44	0.94	
7-8 Aug 58 UNNAMED	S/79	T.D.	ENE 30 GUST 36	NE 16 GUST 26	2.35	
5-7 Aug 59 DOT	WSW/62	H	ESE 45 GUST 56	SE 25 GUST 45	2.99	
17 Sep 63 IRAH	SE/25	T.D.	SE 35 GUST 43	SE 33 GUST 41	1.46	
19-20 Aug 72 DIANA	NE/150	T.S.	ENE 22 GUST 31	E16 GUST 27	0.11	Winds ≥20 Kts recorded only for 1 1/2 hr
19-21 Jul 78 FICO	SW/227	H	ENE 27 GUST 44	E 23 GUST 32	T	
31 Aug-1 Sep 78 MIRIAM	S/329	T.S.	ENE 23 GUST 32	ENE 18 GUST 27	0.02	Enhanced Tradewinds
31 Jul-3 Aug 82 GILMA	S/176	T.D.	ENE 24 GUST 32	E 16 GUST 20	0.06	Enhanced Tradewinds
23 Nov 82 IWA	NW/110	H	SSW 40 GUST 70	SW 37 GUST 61	0.61	

*Honolulu data measured at Honolulu International Airport.

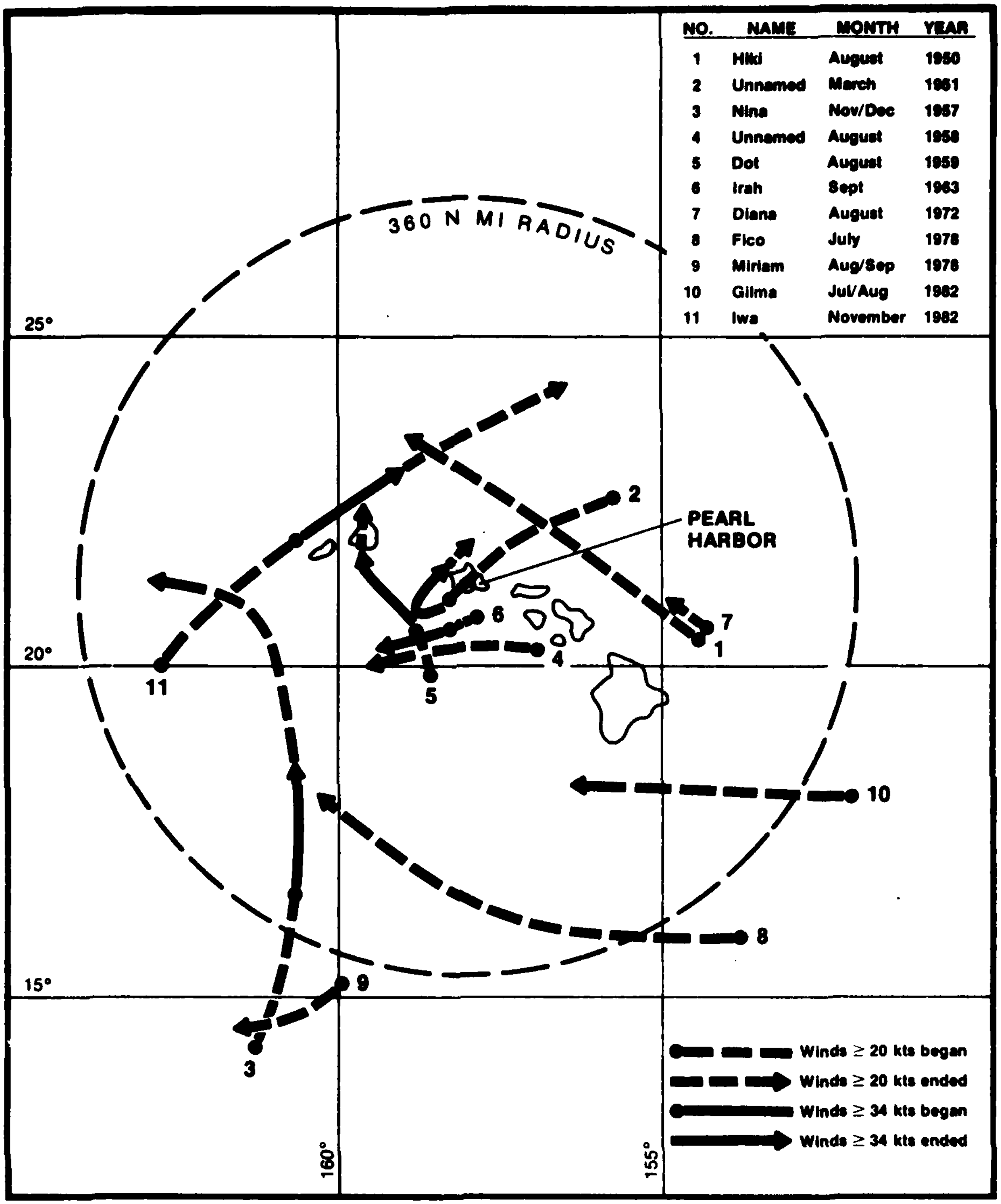

Figure 17. Track segments of 1950-1983 tropical cyclones that passed within 360 n mi of Pearl Harbor and produced sustained winds of 20 kts or greater at NAS Barbers Point or Honolulu International Airport. Sustained winds at NAS Barbers Point remained less than 20 kts during storms 4,7,9 and 10. Of the five instances (2,3,5,6, and 11) when gale force winds (≥34 kts) were recorded at Honolulu International Airport, NAS Barbers Point recorded gale force winds during storms 2,6, and 11.

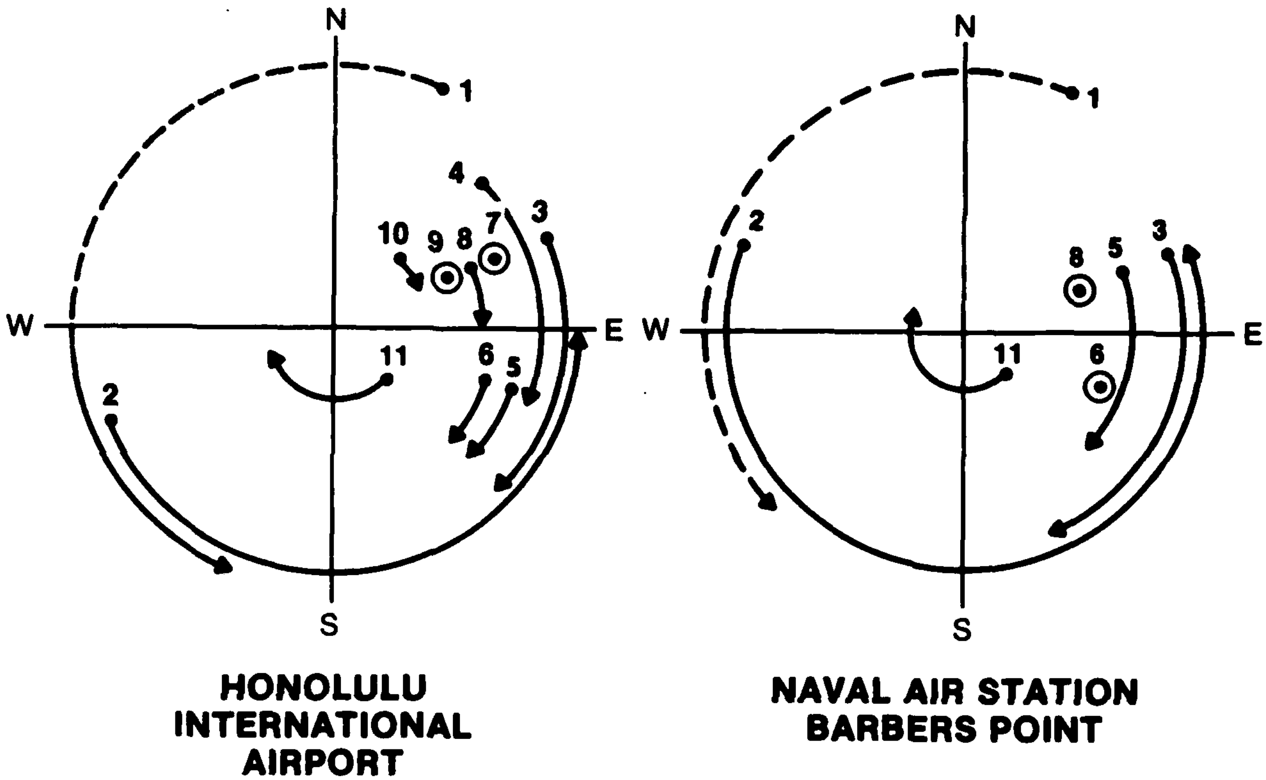

Figure 18. Directions of winds $\geq$20 kts during tropical cyclone passage. Beginning and end of 20 kt winds indicated by dot and arrowhead, respectively. Direction changes during wind speeds less than 20 kts indicated by dashed line. Numbers keyed to storm names in Figure 17. NAS Barbers Point winds did not record sustained wind speeds of 20 kts or more at any time during storms 4,7,9, or 10. O indicates no significant direction change.

recorded from essentially all directions (no northeast directions were recorded at NAS Barbers Point), the predominant direction for the onset of winds $\geq$20 kts is east-northeast, the normal trade wind direction, indicating that many of the increased wind speeds result from storms south of Oahu tightening the pressure gradient over Oahu and thereby enhancing the normal trade wind flow.

Of the four instances where the Hawaiian Islands came under the influence of a hurricane, the last occurrence, Hurricane Iwa in November 1982, is the best documented and the one that caused the most extensive damage to Oahu. While Iwa was, by many standards atypical, it is useful to examine some of the characteristics of the storm to better understand the effects a hurricane can have on the south coast of Oahu.

Hurricane Iwa formed southwest of Oahu near 8.5N 166.0W and initially followed a slow, meandering northward track until about 1800Z on 22 November. As can be seen in Figure 19, the storm then accelerated as it moved north and then northeastward, passing west of Niihau and Kauai near 240300Z. Its closest point of approach to Oahu occurred when it was northwest of the island at approximatly 240430Z and moving at a speed of about 30 knots. Table 3 lists the hourly wind data for selected stations on Oahu for the period 7AM to midnight local time (231700Z-241000Z) on 23 November 1982.

The recorded peak wind gust recorded at NAS Barbers Point was 210/37G61 at 1818 local time/240418Z, while Honolulu Airport recorded a peak of 200/40G70 at 1845 local time/240445Z. Higher sustained wind speeds and peak gusts were recorded elsewhere on the island, but were either at higher elevations or had the wind flow enhanced by

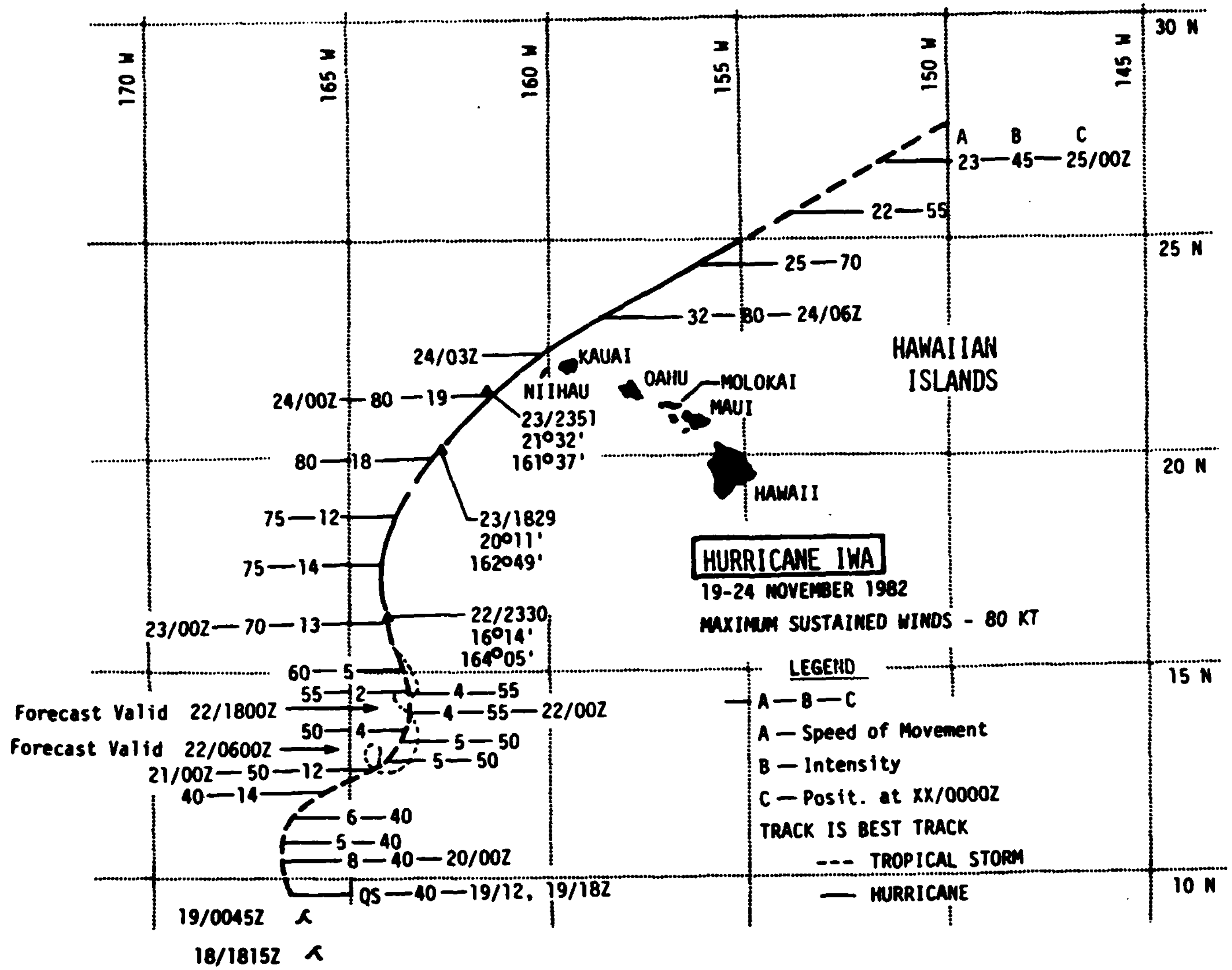

Figure 19. Track of Hurricane Iwa.

TABLE 3. Hourly wind direction and sustained speed and gust (G) on November 23, 1982, 7 AM - midnight. Wind speed in kts.

HOUR		BARBERS POINT	HONOLULU AIRPORT
LOCAL	GMT	DIR/SPD	DIR/SPD
0700	1700	120/10	120/16
0800	1800	130/13	110/20G27
0900	1900	140/16	120/21G29
1000	2000	140/18	120/24G31
1100	2100	140/20	120/21G28
1200	2200	150/20G30	120/25G32
1300	2300	160/27G33	130/26G33
1400	2400	160/25G35	140/25G34
1500	0100	170/30	140/28G37
1600	0200	180/32G44	140/35G45
1700	0300	180/34G44	160/34G47
1800	0400	190/34G47	160/32G47
1900	0500	220/37G52	230/25G44
2000	0600	220/34G42	210/23G34
2100	0700	220/31G45	220/25G36
2200	0800	240/32G40	240/24G34
2300	0900	260/25G31	230/22G33
2400	1000	280/24G29	240/12G28

acceleration on the lee of the mountains, such as occurred at MCAS Kaneohe Bay which recorded a peak of 210/48G80 at 1858 local/240459Z (Chiu, et al., 1983).

As documented by Chiu, et al. (1983), "On Oahu, most of the peak winds occurred between 6:20 pm and 7:00 pm as a squall line passed over the island.... There was not a single case of sustained hurricane force winds on...Oahu..."

Perhaps the most devastating aspect of Hurricane Iwa was the coastal flooding. Kauai suffered the worst effects, with the storm passing just west of the island thereby placing Kauai near the eye of the storm in the dangerous right semicircle. Minor water height rises were recorded on Oahu, but more important on Oahu was the severe wave action from waves generated by the storm.

Water height rises due to storm surge will be discussed in section 4.4 of this document, but insofar as Hurricane Iwa is concerned, the south coast of Kauai experienced a water level rise estimated to be as high as 15 feet. Oahu tide recorders measured rises of just over 2 ft (above predicted tide levels) at Pier 4 in Honolulu Harbor. Also the following was extracted from Haraguchi (1983): "An instrument measuring the water level at Kewalo Basin, located adjacent to Honolulu Harbor, recorded the rise in the ocean caused by Iwa (from Dr. Klaus Wyrtki, University of Hawaii). The water level peaked sharply at about 8:00 pm even though it was a low tide period. ...Dr. Klaus Wyrtki computed the difference between the observed and predicted water level with time...the water level rose sharply to a peak of 41 inches higher than the predicted level at about 8:00 pm on the 23rd."

Ocean waves generated by Hurricane Iwa caused extensive damage on Oahu, including inundation of the central sections of the coast southwest of the Waianae Range as well as oceanfront areas on the south coast of Oahu from Sand Island east to Diamond Head. In all, some 421 acres of land were flooded on Oahu by the combined effects of storm surge and high wave action (U.S. Army Corps of Engineers, 1983).

The large waves generated by Hurricane Iwa caused extensive underwater damage, scouring coral and sand from the bottom and large rocks and coral heads were moved about, some for great distances. A large (30-inch diameter with 3 inch concrete coating) pipe line laid out 2 n mi seaward off Barbers Point and weighted to the bottom by a series of 10-ton concrete blocks was moved sideways about 400 feet. At the same time a "header unit" (a large assembly of pipes, valves, and fittings) which was anchored by 30-ft steel pilings driven full length into the hard coral bottom was pulled out of the bottom and smashed aside. Some authorities express the opinion that the wave action generated turbidity currents which caused extensive underwater damage, the full extent of which is not yet known.

As far as damage within Pearl Harbor and Honolulu Harbors is concerned, Hurricane Iwa did little harm. Relatively little property damage was done by the winds, and the water rises within the harbors (although tide levels are not measured within the confines of Pearl Harbor) was apparently limited to approximately 2 ft. The major impact that the storm had on Pearl Harbor was the hazards its waves posed to ships as they attempted to leave the harbor during the afternoon of the 23rd. Several ships reported waves (variously described as "surf", "breakers", and waves) of heights ranging from 14 ft to 30 ft in the Pearl Harbor Entrance Channel between buoys 1 and 2 and buoys 3 and 4. One sailor was killed, another washed overboard and later recovered on the Honolulu Airport Reef Runway landfill, and others were injured when a departing U.S. Navy ship encountered a large wave near buoys 1 and 2 at approximately 1625 (local time). No reported difficulties were experienced by large vessels at Honolulu Harbor as none tried to leave port. Some damage was incurred within the confines of the harbor due to wind and wave driven debris and inadequate mooring of smaller vessels.

To put Hurricane Iwa in proper perspective, one must realize that Iwa was not a major storm by hurricane standards. The Saffir/Simpson Hurricane Rating Scale (developed by Mr. Herbert Saffir and Dr. Robert Simpson) is a rating scale of hurricanes. Barometric pressure, windspeed and surge height are factors which determine the categories. The Saffir/Simpson Hurricane Scale is shown in Table 4. If windspeeds which were estimated from satellite photographs are used, Iwa would be in Category 1, the weakest (U.S. Army Corps of Engineers, 1983).

Because Hurricane Iwa was not a strong storm by hurricane standards, and passed well to the west of Oahu, it is fair to theorize that a stronger storm passing closer to Oahu would inflict much more damage to the south coast of Oahu.

Hurricane Iwa was atypical with respect to precipitation also. The National Weather Service Office at Honolulu International Airport recorded relatively little rainfall (Table 2), with 2 to 4 inches accumulated in the heavier rainfall areas. Higher rainfall totals would be expected from a "typical" hurricane passage.

TABLE 4. Saffir/Simpson hurricane scale.

Scale Number (Category)	Atmospheric Pressure Millibars	Inches	Winds (MPH)	Storm Surge (Ft)	Damage
1	≥980	≥28.94	74-95	4-5	Minimal
2	965-979	28.50-28.91	96-110	6-8	Moderate
3	945-964	27.91-28.47	111-130	9-12	Extensive
4	920-944	27.17-27.88	131-155	13-18	Extreme
5	<920	<27.17	155+	18+	Catastrophic

4.2.1 Wind and Geographic Effects

The south coast of Oahu is essentially open to wind from approximately 120° clockwise to 270°, and from the north-northwest through the valley between the Waianae and Koolau Ranges. The Koolau Range would afford some protection from winds with a north to northeast component, as would the Waianae Range to the northwest. A possibility does exist, however, for northeasterly wind flow to be enhanced by funnelling through passes in the Koolau Range and cause increased winds in the Honolulu/Pearl Harbor area. The opposite was the case with enhanced southwesterly flow which caused increased wind speeds at MCAS Kaneohe Bay during Hurricane Iwa.

4.2.1.1 Pearl Harbor

In terms of vulnerability to wind damage, a wind with a strong component perpendicular to the normal east-northeasterly trade wind flow would likely cause the most damage since most of the berths have a southwest-northeast orientation and would be most vulnerable to a cross component. As can be seen in Table 2, Hurricane Iwa (November, 1982) is the only storm since 1950 to cause strong winds with a north-south component. While some ships sortied from the harbor, others remained at their berths. One severely tested her mooring lines and the limited tug availability as she was blown away from (versus onto) her berth and was in danger of parting her lines. Tugs were used to push her against her berth and keep her there during the worst of the blow. Considering that only 4 Navy tugs are available, and commercial tug availability from Honolulu Harbor is uncertain, the ability of Pearl Harbor facilities to handle more than 1 or 2 ships with cross-berth wind problems is severely restricted.

4.2.1.2 Honolulu Harbor

The facilities in Honolulu Harbor are random in orientation, so a particular wind direction may not be bothersome to some berths and may cause problems at others. During the passage of Hurricane Iwa, no ships were sortied, and only one commercial vessel experienced significant problems. A container ship, moored at the Matson wharf located on Sand Island just east of the bridge, was blown off her berth by the southerly winds, but tugs were sent to her aid and were used to keep her against the wharf for the remainder of the storm. The harbor is more or less exposed to southerly winds, but is afforded limited protection from northeast and easterly winds by the buildings of Honolulu.

4.2.1.3 NAS Barbers Point

NAS Barbers Point lies on a sloping promontory near the south end of the Waianae Range, making it exposed to winds from northeast clockwise through west. As can be seen in Table 2, in all cases but one, NAS Barbers Point wind speeds were less than those recorded at Honolulu International Airport (no attempt has been made to apply corrections for differing heights of anemometers above sea level). The primary concern relative to wind damage at NAS Barbers Point is damage to aircraft. Several squadrons are assigned there and the aircraft must be flown to a more secure airfield during a hurricane threat, be securely tied down into the wind or be placed out of the wind in a hangar. If the wind is expected to shift directions while the wind force is still strong, severe complications result; the aircraft will not always be oriented into the wind and the aircraft direction is difficult to change during strong winds. There is no easy solution to the problem other than sending the aircraft that cannot be hangared out of the wind to other airfields out of harm's way.

4.3 WAVE ACTION

4.3.1 Pearl Harbor

Except for the entrance channel, Pearl Harbor is well protected from ocean waves. The unique fan shape of the harbor limits fetch lengths within the confines of the harbor to 2.5 n mi or less. Table 5 lists the various water areas around the harbor and the wind-driven waves that could be expected with the wind directions and speeds given. The wave heights listed assume a relatively flat bottom at or near project depths and are derived from the curves presented in the U.S. Army Corps of Engineers' Shore Protection Manual (1973). They are provided as a guide only and do not consider wave interaction from one part of the harbor with another nor increased water levels due to storm surge or other causes.

As Hurricane Iwa proved, wave action in the lower reaches of the Pearl Harbor Entrance Channel can pose a serious hazard to vessels transiting the channel in strong wind with a southerly component. The seaward limit of the channel lies where the water shallows rapidly from depths exceeding 60 meters (197 ft) to less than 16 meters (52 ft) in a short distance, about 400 yards. Numerous reports during the sortie from Pearl Harbor in advance of Hurricane Iwa described the waves in the channel near buoys 1 and 2 (the entrance markers for the channel) as being up to 30 ft high, and large waves described as "surf" and "breakers" were reported in the channel near buoys 3 and 4, about 0.75 n mi north-northwest from buoys 1 and 2.

TABLE 5. Wind wave heights in Pearl Harbor (in feet).

LOCATION	Wind Direction (degrees from)	Wind Speed in knots (MPH) 30(35)	50(58)	70(80)	90(103)
Pearl Harbor Entrance West of Naval Shipyard and Hickam AFB	360	2.5	4.0	6.0	7.5
Magazine Loch	220	1.3	2.3	3.3	4.5
Across South Channel to/from Southeast Loch/ Merry Loch/Quarry Loch and Ford Island	300/120	1.8	3.0	4.4	6.0
North Channel	230/050	2.4	4.0	5.4	7.0
Middle Loch	340/160	2.5	4.2	6.0	8.0
East Loch north and	305/125	2.2	3.8	5.2	7.0
east of Ford Island	360/180	1.8	3.0	4.3	6.0
West Loch					
Lower reaches	325/145	1.8	3.0	4.3	6.0
Upper reaches	320/140	2.0	3.5	5.1	7.0
South Channel; Area Bay to Drydocks 1-3.	210/030	2.3	4.0	5.5	7.2
South Channel; Kilo berths to Nevada Point	245/065	2.5	4.0	5.2	8.0

4.3.2 Honolulu Harbor

Except for that portion of the Main Basin south of Aloha Tower (Figure 7), Honolulu Harbor is well protected from ocean waves. Fetch length is limited to a maximum of 1.5 n mi, and is considerably less in most directions. Table 6 lists the various areas of the harbor and the wind driven waves that could be expected with the directions and speeds given. The wave heights listed assume a relatively flat bottom at or near project depths and are derived from the curves presented in the U.S. Army Corps of Engineers' Shore Protection Manual (1973). They are provided as a guide only and do not consider wave interaction within the harbor nor increased water levels due to storm surge or other causes.

While there were no reported eyewitness accounts of enhanced ocean waves near the entrance to Honolulu Harbor Channel during Hurricane Iwa such as those that were reported for Pearl Harbor Channel, the bathymetry near both channel entrances is similar, so the same conditions likely existed.

4.4 STORM SURGE

In the words of Gilmore (1983), "storm surge may be visualized as a raised dome of water, moving with the storm, and centered a few miles to the right of its path. The dome height is related to local pressure (i.e. an (inverted) barometer effect dependent on the intensity of the storm) and to local winds. Other significant contributing factors are storm speed, direction of approach with respect to the shoreline, bottom topography, and coincidence with astronomical tide."

TABLE 6. Wind wave heights in Honolulu Harbor (in feet).

LOCATION	Wind Direction (degrees from)	Wind Speed in Knots (MPH) 30(35)	50(58)	70(80)	90(103)
Main Basin; Harbor entrance to area north of Aloha Tower	185/005	1.4*	2.3*	3.4*	4.5*
	130/310	1.0	1.5	2.3	3.0
	250/070	1.0	1.4	2.2	2.9
Main Basin to Kapalama Basin	300/120	2.0	3.4	5.0	6.5
Kapalama Basin	090/270	1.5	2.5	3.9	4.9
	180/360	1.3	2.2	3.0	4.1

*Does not consider ocean waves entering the harbor during periods of southerly wind.

"The worst circumstances (Harris, 1963 and Pore and Barrientos, 1976) would include:

(1) An intense storm approaching perpendicular to the coast with the harbor within 30 n mi to the right of the storm's track.

(2) Broad, shallow, slowly shoaling bathymetry.

(3) Coincidence with high astronomical tide."

The first and third circumstance outlined above are, of course, determined by factors such as time and storm location, and would change with each storm occurrence. The second, however, is essentially fixed; the bathymetry of a shoreline, on a broad scale, remains largely unchanged. The south coast of Oahu, on which Pearl and Honolulu Harbors are located, does not fit into the worst case bathymetry category because the coast has a narrow shelf on the outer edge of which the water deepens rapidly to great depths. But history has proven that Oahu is nevertheless subject to storm surges.

As was discussed in Section 4.2, the most extensively documented occurrence of storm surge in the Hawaiian Islands came with Hurricane Iwa. Kauai and Niihau bore the brunt of the storms fury, with water rises as high as 15 ft estimated on Kauai, based on still water marks on interior walls of inundated buildings. Documented heights are somewhat lower, with a crest of 8.7 ft above mean sea-level recorded on a crest gage at the estuary of the Waimea River on the southwest coast of Kauai (Cox, 1984). The effects of significant precipitation runoff through the estuary would have to be subtracted from the crest figure. According to

Cox (1984), "On the basis of the record, then, all that can be said is that the storm surge in the Waimea estuary was less than 8.7 ft. msl." A tide gage at Nawiliwili Harbor on the relatively protected (from Hurricane Iwa) east coast of Kauai recorded a comparatively small rise of only about 1.4 ft.

The south coast of Oahu, which is located some 90-n mi east-southeast of the east coast of Kauai, experienced less significant water level rises, and there was considerable variation in the rises observed. Pearl Harbor, which has no water level recorder, had a rise of 1 to 2 ft according to harbor personnel. Honolulu Harbor recorded a rise of just over 2 ft above the predicted level, measured at Pier 4, just inside the harbor on the east side of the main channel. Kewalo Basin, located approximately 0.7 n mi east of the Honolulu Harbor Channel (Figure 7) recorded a rise of 41 inches above the predicted level (Haraguchi, 1983). One undocumented account from an eyewitness who was near the beachfront at the Chevron Oil Refinery, located on the west side of the Barbers Point promontory, reported a rise estimated to be 5 to 6 ft above mean lower low water for that location. The water rise caught him by surprise as he was observing wave action on the beach and he had to run through a foot of water to reach the safety of higher ground. Wave action subsequently damaged the sea wall and washed large boulders some 500 ft into Chevron's yard.

A second eyewitness account is less dramatic, but nevertheless indicates a significant water rise. Kuapa Pond, located just west of Koko Head (Figure 4) was observed to rise about 2.8 ft above normally expected levels at 1900 and 2200 on 23 November (Cox, 1984).

As of this writing no storm surge studies have been done that would predict the storm surge values that could be expected on Oahu with a given storm intensity and trajectory. Oahu County Civil Defense (1984) refers to "Federal Studies" in "progress in attempts to develop reliable predictive models..." which will be used to "prepare a comprehensive hurricane response plan which is scheduled for completion in the latter part of 1985." In the meantime estimates must be used.

The same document by Oahu County Civil Defense cites a scenario that was developed for a joint National Weather Service/Civil Defense exercise which was conducted in 1972. The storm hypothesized "was assumed to approach Oahu from the southeast and that its center would pass over or near Barbers Point. The storm contained maximum winds of 110 miles per hour gusts to 125 mph." This was a "worst possible scenario since it would bring Oahu, and particularly the Honolulu area, under the storm's northeastern quadrant, where winds, storm surge, and rainfall are usually greatest."

In addition to water level rises due to storm surge in the above "worst case" scenario, Oahu County Civil Defense theorizes that "the prolonged southerly swell would also raise water levels within Honolulu and Pearl Harbor, and create bores (small tidal waves) and surges in the harbor channels." Plus, some flooding could be expected from the torrential rainfall accompanying the storm, which may exceed 3 inches per hour and/or 18 inches or more in a 24-hour period.

The storm surge inundation area as defined for civil defense evacuation purposes includes "those shoreline areas of Oahu less than 20 feet above mean sea level in elevation...." Water levels of this magnitude are admittedly extreme, but must be considered in a worst case scenario. Most of the naval installations surrounding Pearl Harbor would be inundated, as would the Honolulu Harbor area. As a matter of fact, a 15 ft rise would inundate most harbor facilities; certainly all of the piers and wharves at both locations. A 20 ft rise would flood NAS Barbers Point from the beach to the runway intersection, and wave action on top of the surge would drive the water even further inland.

During discussions with Naval Shipyard personnel, it was determined that a water rise of 8 ft above mean low water would top the gates on the drydocks and, obviously, create serious flooding problems. Since the maximum astronomical tidal rise in Pearl Harbor is near 2.5 ft, a surge height of only 5.5 ft superimposed on an astronomical high tide could start to flood the drydocks.

The following excerpt from the Oahu County Civil Defense Basic Hurricane Evacuation Plan (draft copy, in preparation) is pertinent to this evaluation of Pearl and Honolulu Harbors:

"Storm Surge on Oahu's Coastal Areas.

1. The storm surge is a complex phenomenon that is not completely understood and difficult to predict using existing models. Neither storm surge theory, nor information observed elsewhere, is of significant assistance in anticipating the height or other characteristics of storm surge along Oahu's shorelines. This remains one of the most serious unknowns concerning the impact of a hurricane on coastal areas of the state."

2. However, certain things are known. Reefs afford no real protection against the storm surge. As the water level rises, reefs will be submerged to greater than normal depths enabling waves to come further toward shore before breaking. Places having "shore breaks" will find the surf zone reaching well inland of the beach."

3. In areas previously affected by high swell, flooding will become much more severe. Waves will drive in with sufficient force to threaten structural damage, and the inundation zone will advance far inland."

4. High water will propagate into semi-enclosed areas like Pearl Harbor and Honolulu Harbor. At the same time, the storm's on-shore winds will pile water against coasts and the downwind shores of bays, harbors, and estuaries."

5. It can be assumed from the bathymetry and topography of the area that a storm surge of only a few feet will raise water levels high enough to cause widespread inundation in many coastal districts. Augmented by the efforts of waves driven onshore by hurricane winds and torrential rain runoff, storm surge has the potential for widespread destruction by both water and flooding."

The mean tidal range on the coast from Honolulu to Barbers Point is approximately 1.9 ft with an extreme range of 2.3 ft under usual conditions. According to U.S. Army Corps of Engineers (1980), the lowest tide on record is -1.15 ft and the highest is +3.1 ft. All of the preceding heights use a zero reference of mean lower low water.

The tidal current floods west and ebbs east along the coast between Makapuu Point and Honolulu. In the vicinity of Honolulu an east counterflow along the edge of the reef accompanies the westerly flood. There is a general west current along the coast between Honolulu and Barbers Point with velocities up to 0.8 kt, setting west, measured off the point, with greater velocities reported. Strong west currents have been reported off Honolulu. Currents setting toward all four quadrants and having velocities up to 1 kt have been observed 3 n mi southwest of Diamond Head (U.S. Department of Commerce, 1981 and U.S. Army Corps of Engineers, 1980).

5. THE DECISION TO EVADE OR REMAIN IN PORT

Instructions for hurricane preparedness by Naval activities on Oahu are contained in COMNAVBASEPEARLINST 3440.7, The Hawaiian Region Disaster Preparedness Program Manual. Conditions of readiness in the Hawaiian Islands will be set and secured by COMNAVBASE PEARL. The appropriate conditions of readiness for activities in the COMNAVBASE PEARL area will be set when sustained winds of fifty (50) knots or more are expected as follows:

Storm (Tropical Cyclone) Condition IV - within seventy-two (72) hours.

Storm (Tropical Cyclone) Condition III - within forty-eight (48) hours.

Storm (Tropical Cyclone) Condition II - within twenty-four (24) hours.

Storm (Tropical Cyclone) Condition I - within twelve (12) hours.

Note: At COMNAVBASE PEARL there is no distinction between types of tropical cyclones, i.e. hurricanes vs. tropical storms, etc.; the 50-kt wind criterion is the only one used for readiness conditions.

When a tropical cyclone approaches, decisions regarding precautionary measures must be timely. Action should be based on consideration of four general factors:

vessel characteristics, harbor conditions and available berthing, the latest tropical cyclone warning/forecast, and storm climatology/history. Individual vessel factors are best determined by those responsible for each vessel. Vessel characteristics, in addition to seaworthiness, include such factors as moored or anchored location and tug and/or pilot needs/availability.

5.1 PRECAUTIONARY ACTIONS

5.1.1 Ships

For seaworthy vessels, precautionary actions should include anything that would enhance a vessels ability to get underway without undue delay. The action list could include, but certainly not be limited to:

Ensuring that adequate fuel is onboard to evade successfully should a sortie be directed.

Reviewing the Recall Bill, as necessary, to ensure that required personnel are available when needed.

Ensuring that sufficient heavy weather gear, including heavy mooring tackle, is onboard and immediately available.

Pre-planning viable evasion routes in view of the existing and forecast storm threat.

Ships that are not seaworthy should be made ready to move to the most secure berths available to ride out the storm.

If it is apparent that the ships to remain at Pearl Harbor will overtax the capabilities of the available tug resources, consideration should be given to arranging for civilian tugs, as necessary, to be moved to Pearl Harbor before the onset of heavy winds and/or seas.

5.1.2 Aircraft

The precautionary actions for aviation activities would be much the same as those taken for ships, and would have the same basic goal, an unhampered ability to disperse to areas away from the storms track. Aircraft that can not be flown should be made ready to move to designated areas where they can be securely tied down or otherwise protected.

5.2 THREAT ASSESSMENT

A review of the tropical cyclone threat analysis presented in Section 4 of this evaluation indicates that, while the south coast of Oahu is not seriously affected by tropical cyclones on a routine basis, the area is at considerable risk to damage from an occasional storm, and wind, ocean waves, and storm surge are all factors that must be considered. The absence of sheltered berths or heavy weather anchorages makes evasion at sea the safest course of action for all seaworthy deep-draft vessels and submarines as soon as it can be determined that a storm poses a threat to the area. Submarines are included because, although they did not sortie in advance of Hurricane Iwa and suffered no damage, they are considered vulnerable to the vagaries of wind and storm surge and should avoid potential damage by leaving the harbor. Since deep water is nearby, the cost of sortieing is small compared to the risk of loss. Early assessment of each potential threat is essential, and should be related to the setting of conditions of readiness by COMNAVBASE PEARL, and conducted using current advisories and forecasts issued by the Navy as well as the climatology presented herein.

5.3 THREAT SOURCES

Figures 10 through 15 clearly show that tropical cyclones approaching from the east-southeast have a greater chance of approaching Pearl Harbor than do storms from other directions, with a secondary threat coming from the south-southwest. As was discussed in Section 4.4, the worst possible scenario for the coast of Oahu would have an intense tropical cyclone approach from the southeast, with its center passing over or near Barbers Point. This track would bring Pearl and Honolulu Harbors and NAS Barbers Point near the eye of the storm and bring the stongest winds--those in the storm's dangerous right front quadrant--to bear on the area. Additionally, the track would place Pearl and Honolulu Harbors in a potentially devastating storm situation. Any developed storm with a track that has a significant south to north component and passes within 120 n mi to the west of Pearl Harbor would pose a storm surge threat to the south coast of Oahu. The threat would increase with the strength of the storm and the closeness of the passage. The 120 n mi figure is somewhat arbitrary since it is conceivable that an intense storm passing a greater distance from Pearl Harbor could cause water height rises, but such rises would likely be caused by wave set-up rather than true storm surge. Also, a less intense or smaller storm could pass closer than 120 n mi without causing storm surge in the area.

A storm passing to the east of Oahu would not be expected to generate a storm surge on Oahu, and may even cause a temporary reduction in water level in Pearl Harbor. The latter effect would be more likely with a slow moving storm that caused prolonged northerly winds across the area. The effects of the storm's wind would also be minimized due to Oahu being on the relatively weak left side of the storm.

The individual storm intensity and speed of movement will affect the extent of damage which can be expected from any given storm. As a general rule, any storm which approaches from the east at a latitude sufficiently far enough south so that the main storm circulation does not get weakened by the islands of Hawaii and Maui is a potential threat. Westward moving storms at latitudes of 19N or higher pose a lesser threat because they stand a good chance of being weakened by the other islands before they reach Oahu or may pass up the windward side of the islands, placing Oahu on the relatively weak left side of the storm. Storms forming in or moving northward through the waters south of Pearl Harbor must be considered as potential threats; Hurricanes Nina, Dot, and Iwa all came from this southerly direction prior to affecting Oahu. The months of maximum threat are July through September, with August being the greatest threat month. The occurrence of Hurricane Iwa in November, however, has proven that the "off season" months can also be hazardous.

5.4 EVADING THE TROPICAL CYCLONE

5.4.1 Evasion at Sea

Evasion at sea is the recommended course of action for all seaworthy deep-draft vessels and submarines when the south coast of Oahu is threatened by an intense tropical storm ($\geq$50 kt wind) or hurricane approaching from a southerly direction (southeast through southwest) and Pearl Harbor falls within 120 n mi of the forecast 50 kt wind area. Evasion should be considered for other storm situations on a case by case basis as the circumstances dictate. In any case, ships should exit the harbor channels well prior to the onset of 30 kt winds due to the narrow channel and the tendency for seas to build up where the water shallows near buoys 1 and 2. Timing of the decision to evade is affected by:

(1) The forward speed of the tropical cyclone.

(2) The radius of hazardous winds and seas that can impact on a vessel's ability to reach open water and then maneuver to evade.

(3) The elapsed time to make preparation to get underway.

(4) The elapsed time to reach open water.

For example:

> A worst case situation would be an intense tropical cyclone approaching Pearl Harbor from the southeast. Assume 4 hours are required to recall personnel from liberty and make preparations to get underway after the decision to evade or the order to sortie is given. Approximately 1 hour is required to reach open sea. A tropical cyclone approaching at an average speed of 10 kt will have moved 50 n mi closer to Pearl Harbor by the time sea room is attained. Add to this the 30-kt wind radius of the storm, say 150 n mi. The sum of these values (50 + 150) gives 200 n mi, or 20 hours at a 10 kt SOA, as the minimum tropical cyclone displacement from Pearl Harbor in distance or time when the decision must be made to evade at sea without difficulty. A greater margin may be applicable depending on tropical cyclone speed and intensity, and vessel capability.

Since readiness conditions at Pearl Harbor are not set for gale force winds, it is apparent that evasion plans should be executed soon after COMNAVBASE PEARL has set Storm (Tropical Cyclone) Condition II, $\geq$50 kt winds expected within 24 hours. Delay wagers the accuracy of information on the storms forecast behavior against mounting risks of heavy weather damage.

Once sea room is attained, the tactics employed to avoid the effects of the storm will depend largely on the location of and forecast for the threatening tropical cyclone and the characteristics of the vessel. Up-to-date information is vital to sound decision making. Satellite technology and other advances make tropical cyclone location and intensity information accurate and timely. Forecasts and warnings are issued at 6-hourly intervals, with updates issued as necessary to reflect important changes in location, movement, and intensity. Ship Commanding Officers or Masters with access to these forecasts and warnings are in the best possible position to modify evasion routes and tactics to successfully evade the tropical cyclone.

A cardinal rule of seamanship is to avoid the dangerous right hand semicircle of a tropical cyclone. The following guidelines are offered.

(1) <u>For tropical cyclones approaching from the east</u>: After an early departure, steam southwest to a latitude south of the storm center. While it is not unheard of for a tropical cyclone to move to a lower latitude, such occurrences are rare and an early departure should insure adequate time to stay clear of the storm if it would tend to move southward.

(2) <u>For tropical cyclones approaching from south or southeast</u>: After an early departure, steam eastward and remain in the lee of the Hawaiian Islands until the storm is out of the area. If the tropical cyclone should recurve northeastward while south of Oahu, it may be necessary to steam southeastward to clear the storm. This is perhaps the most dangerous of the listed evasion maneuvers, since the ship is being committed to remain in the right semicircle of the storm's circulation. Extreme caution must be exercised

to ensure adequate clearance from the storm's center is maintained. A westward evasion course after clearing the harbor entrance channel is a possible course of action but, since climatology shows that the majority of storms will follow a track with a westward component rather than recurve to the northeast, the risk of a prolonged encounter is increased.

(3) For tropical cyclones approaching from southwest or west: After an early departure, steam eastward to the east side of the Hawaiian Islands, then southeast and south until a latitude south of the storm center is reached, remaining clear of the storm until it is out of the area.

(4) For submarines: Depart the harbor sufficiently early to avoid any significant buildup of seas near the channel entrance. After sea room is attained, submerge to a depth equal to at least one-half the wavelength of the longest waves forecast. Since wavelength is closely related to wave period, a comparable guideline is that a depth of 300 ft will avoid most motion caused by waves with an 11 second period. Similarly, depths of 400 ft and 500 ft will avoid motion caused by waves with periods of 12.5 and 14 seconds respectively. Correspondingly greater depths would be required for waves with longer periods.

5.4.2 AIRCRAFT DISPERSAL

Naval Air Station, Barbers Point is home to several aircraft squadrons, with over 50 large turboprop aircraft assigned in addition to miscellaneous smaller aircraft and helicopters. Hangar space or other protection is not available for all aircraft during tropical cyclone threats, so the safest method of protecting the large aircraft is to fly them to other airfields out of the path of the storm. The U.S. Navy airfields that are generally used as dispersal points are NAF Midway Island, NAS Moffett Field, California, and NAS Whidbey Island, Washington. The large number of aircraft involved dictate that more than one dispersal point be used.

Commercial airports such as Hilo may also be appropriate as dispersal points. First priority on space would be given to local commercial aircraft which are unable to reach the mainland because auxiliary fuel tanks are installed only for ferrying to the islands and then permanently removed for local intra-island service.

Because the aircraft should be launched before field conditions deteriorate with the approach of the storm, early decision making is mandatory. Air traffic control limitations dictate a minimum of 4 hours is required to launch all of the aircraft once the dispersal has begun, so the dispersal should begin at least 4 hours prior to the earliest possible onset of 30 kt winds. In any case, the last aircraft to be flown away should be airborne before 30 kt winds commence.

The layout of the Barbers Point runway complex minimizes crosswind problems. A comparison of the primary runway (runway 04 left and right and 22 left and right) headings of 044°/224° magnetic (magnetic variation about 11°30'E) with the directions of onset of 20 kt winds shown in Figure 18 indicates that the onset of most of the stronger winds in advance of a tropical cyclone will occur from a direction that is nearly parallel to the runway. A second, single runway 11/29 would accommodate those crosswind situations that may develop.

5.5 REMAINING IN HARBOR

Staying in port at Pearl or Honolulu Harbor is an option that should be considered only in secondary threat situations or in those instances when a vessel is incapable of getting underway for evasion at sea. Secondary threat situations include:

(1) A tropical cyclone forming so close at hand that evasive action is precluded.

(2) A weak tropical storm (winds $\leq$45 kt) or tropical depression is approaching Pearl Harbor and forecast <u>not</u> to intensify.

(3) A tropical cyclone with winds $\geq$50 kt is forecast to pass sufficiently far from Pearl Harbor so that the 50 kt wind area misses the south coast of Oahu by at least 120 n mi.

Should the decision be made to remain in port, it should be borne in mind that the ship will be exposed to dangers beyond that of wind and storm surge. Other vessels may be broken loose from their moorings and become floating hazards. Also, the danger is everpresent that a damaged or sunken vessel could block the narrow ship channels and trap ships in the port for some time after the storm has passed.

5.6 USE OF ANCHORAGES

No anchorages near Oahu are recommended as heavy weather anchorages.

5.7 RETURNING TO HARBOR

After the passage of a tropical cyclone, entering a harbor may present hazards. Channel markers and other navigation aids may have shifted position or become otherwise unreliable. There may be shoaling in the channel, wrecks or other debris in or near the channel, and damage to piers and wharves. Alongside services may be disrupted so that electrical power, water, and telephone lines may not be available. Extreme caution should be exercised and advance coordination is strongly recommended before returning to harbor.

5.8 ADVICE FOR SMALL CRAFT

Since there are no recommended small craft hurricane mooring facilities on Oahu, small craft should be removed from the water and securely fastened against wind damage at a location above predicted high water levels. Short of removing from the water, the only action that may afford some protection (short of leaving the area) is to move the craft to the side of the island forecast to be in the lee of the strongest winds.

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32GG2	Fleet Ocean Tug PAC (ATF)
32H2	Fast Combat Support Ship PAC (AOE)
32MM	Guided Missile Ship (AVM)
32N2	Oiler PAC (AO)

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32QQ2	Salvage and Rescue Ship PAC (ATS)
32S2	Repair Ship PAC (AR)
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